

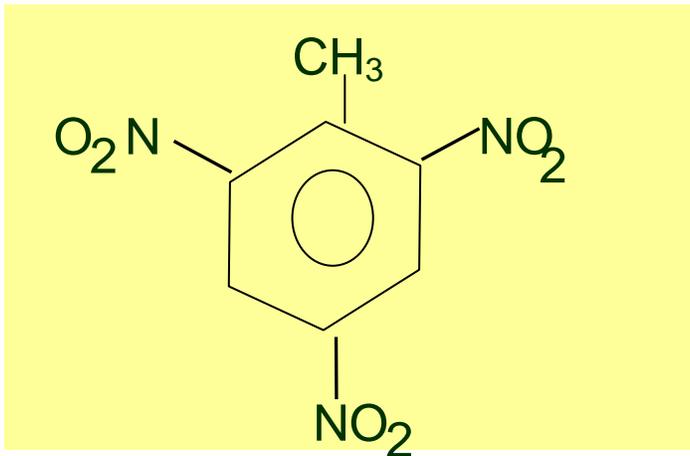
## CHAPTER - 1

### INTRODUCTION

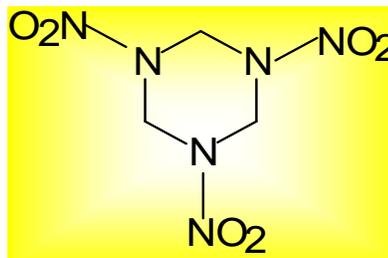
Currently, melt cast explosive compositions based on 2, 4, 6-Trinitrotoluene (TNT) are used for wide range of ordnances. TNT was inducted in explosive systems during world war I. Major advantage of TNT is wide difference in its melting point and decomposition/ignition temperature rendering it possible to safely melt and cast it into munitions/warheads. It also has advantage of high chemical stability and insensitivity to mechanical stimuli (impact/friction) as well as shock wave.

TNT is preferably used in combination with powerful high explosive compounds like cyclo-trimethylenetrinitramine (RDX) and cyclo-tetra methylenetetranitramine (HMX) to realize enhanced power. RDX and HMX have advantage of higher density, oxygen balance and heat of formation compared to TNT, resulting in enhanced energy release during explosion process leading to higher velocity of detonation (VOD). Characteristics of predominantly used high explosives are summarized in Table 1.1.

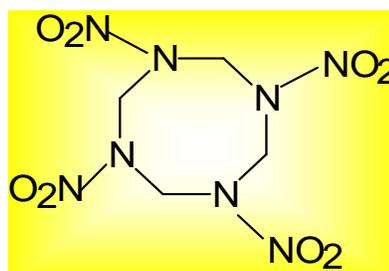
TNT based melt cast explosive compositions remain preferred choice even in present scenario due to availability of TNT at economical cost and ease of processing of the compositions in standard melt cast facilities existing all over the globe for wide range of artillery shells, tank ammunitions and missile warheads.



**2, 4, 6-Trinitrotoluene (TNT)**



**Cyclotrimethylenetrinitramine (RDX)**



**Cyclotetramethylenetetranitramine (HMX)**

## 1.1 Melt cast explosives: Current status

RDX and HMX in combination with TNT often referred as Hexolite and Octol have found wide application in shaped charges and fragment creating munitions as well as missile warheads to destroy tactical/strategic targets.

**Table 1.1: Characteristics of widely used High Explosives [1]**

Explosive	Molecular weight	Heat of formation (kJ/mol)	VOD		Detonation pressure	
			Charge density (g/cm <sup>3</sup> )	Velocity (m/s)	Charge density (g/cm <sup>3</sup> )	Pressure (kbar)
TNT	227.1	-62.7	1.64	6950	1.63	189.1
PETN	316.2	-537.9	1.77	8310	1.77	320
TETRYL	287	+19.5	1.73	7720	1.68	239
RDX	222.1	+61.48	1.806	8950	1.80	341
HMX	296.2	+74.94	1.89	9110	1.90	395

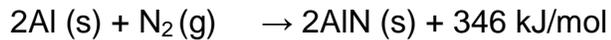
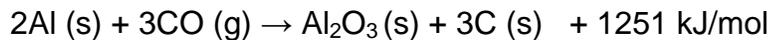
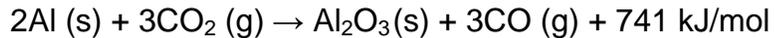
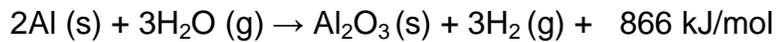
Composition B comprising RDX/TNT/Wax in 60/40/1 combination and Octol comprising HMX/TNT in 75/25 ratio are being used as filling in munitions/warheads for more than 65 years [2]. Performance parameters of selected TNT based explosives compositions are summarized in Table 1.2.

Aluminized melt cast formulations delivering an enhanced blast effect due to secondary combustion of aluminum (Al), beyond detonation zone are extensively used in blast ammunition/warheads.

**Table 1.2: TNT based melt cast compositions [1]**

Explosive Composition	VOD		Detonation pressure	
	Charge density (g/cm <sup>3</sup> )	Velocity (m/s)	Charge density (g/cm <sup>3</sup> )	Pressure (kbar)
PETN/TNT 50/50 (Pentolite)	1.64	7530	1.66	280
RDX/TNT/Wax 60/40/1 (Composition B)	1.72	7990	1.71	292.2
HMX/TNT 75/25 (Octol)	1.81	8364	1.82	343.7

The detonation products of CHNO explosive (CO, CO<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub> etc.) generated at high temperature during first stage of detonation react with aluminum, producing energy due to the exothermic reactions. As a consequence, Al increases duration of explosive detonation pressure whereas delivered VOD and detonation pressure of this class of composition are brought down compared to corresponding non aluminized composition due to inert nature of Al. Cook and Co-workers [3] reported low brisance effect due to incomplete reaction at C-J plane and high blast potential due to after burning of Al. The basic chemical processes involving Al in the explosion phenomenon, resulting in the blast effect, are summarized in a recently published review [4]. It has been established that addition of aluminum up to 20% by weight adds to the destructive power in air blast.



For underwater ammunition/warheads compositions containing more than 20% aluminum also find application. Explosive when detonated in water, blast pressure decay is slower due to higher density of water compared to air (800 times). During underwater explosion, shock wave accounts for 46% of available energy and explosion products form a large gaseous bubble and the residual energy remains with the bubble. The bubble causes damage due to its expansion for a longer period of time and on its bursting over the surface of the target. Peak pressure generated during the underwater explosion phenomenon acts on the target for a comparatively longer duration resulting in 'water hammer effect' due to the transfer of kinetic energy of shock wave to the moving mass of water. The partition of the total available energy between the shock wave energy (46%), bubble energy (48%) with the dissipation of residual energy (06%) in water.

Mix of TNT, aluminum and ammonium nitrate (AN) known as Ammonal (22/11/67 AN/Al/TNT), Minol (40/20/40 AN/Al/TNT), and Tritonol (80/20 TNT/Al) were used during World War I due to shortage of TNT. However, these compositions did not find much attention at later stage

due to advent of more powerful and relatively safer explosive compounds RDX/HMX.

Well-reported aluminized explosive composition Tritonal contains 80% TNT and 20% flaked Al. It was developed and standardized in USA during World War II for realizing improved blast ammunition. Tritonal is a general-purpose composition for fragmentation and air-blast applications, particularly in navy and air force bombs [4]. Torpex belonging to this class also came into prominence by the end of World War II, however its use is forbidden by U.S.Navy because of the accidents occurred during World War II [2]. Al incorporated Octol, designated as HTA, finds application for its blast capability combined with brisance.

Currently, Dentex, Torpex, H-6, HBX-1, and HBX-3 are widely used aluminized cyclotol (RDX/TNT) compositions. Dentex, Torpex, and H-6 are general purpose explosive compositions, like tritonal, whereas HBX-1 and HBX-3 find application in underwater mines and torpedoes. HBX-3 is a preferred choice for achieving the maximum bubble energy. Characteristics of selected aluminized melt cast high explosive compositions are summarized in Table 1.3.

Although TNT based Melt cast high explosive compositions are widely used in all classes of warhead and ammunition, this class of explosives has limited energy potential due to restriction on RDX/HMX content in compositions from processing point of view. Further, these compositions are prone to accidental initiation because of sensitivity of

RDX/HMX and if not processed without flaw. During processing of melt cast compositions, solidification of liquid TNT is accompanied with contraction in volume to the extent of 10% due to wide differences in density of both the phases (1.48 and 1.654 g/cm<sup>3</sup> respectively) [6]. It may lead to defects like discontinuities and central/annular cavities in the explosive charge which may act as potential hotspots for premature initiation under influence of set-back forces experienced by the charge on deployment from gun/missile launcher as well as unanticipated shock during missile cruise phase.

**Table 1.3: Characteristics of aluminized melt cast high explosive compositions**

Composition	Density (g/cm <sup>3</sup> )	VOD (m/s)	Detonation pressure (GPa)	Peak pressure (kg/cm <sup>2</sup> )	Impulse (kg.ms/cm <sup>2</sup> )
Tritonal(TNT/Al80/20) [4]	1.72	6520	20.9	-----	-----
H-6 (RDX/TNT/Al/Wax 45.1/29.2/21/4.7) [5]	1.76	7490	24.5	5.03	1.51
Dentex (RDX/TNT/Al/Wax 48.5/33/5/18/1added)[5]	1.81	7780	-----	5.27	1.45
Torpex-4A (RDX/TNT/Al/Wax added : 20/55/25/3) [4]	1.76	7125	21.8	-----	-----
Topex-4B (RDX/TNT/Al/Wax 40.5/37.5/18/4) [5]	1.76	6700	-----	4.25	1.47
HBX-1: (RDX/TNT/Al/D2Wax 40.4/37.8/17.1/4.7) [4]	1.712	7310	22	-----	-----
HBX-3: (RDX/TNT/Al/D2Wax 31.3/29.0/34.8/4.9) [4]	1.85	7530	20.6	-----	-----
HTA (HMX/TNT/Al/CaCl <sub>2</sub> 49/29/22/0.5 added) [5]	1.90	7866	-----	5.29	1.97

The defects in melt cast charges are minimized by adopting use of header/dolly, hot probing and preheating the mould/casing as well as and imparting vibrations and controlled cooling/annealing. The explosive melt is also subjected to degassing to avoid porosity. Bonding of the explosive charge to the ammunition casing is enhanced by uniform coating with bituminous paint. It is also observed that TNT tends to creep out of its casing through screw threads/joints (Exudation) during prolonged storage due to thermal cycling of ammunition/warheads leading to possibility of fire/explosion hazards on handling/operation. Exudation is attributed to presence of minor impurities of unsymmetrical isomers of TNT and di-nitro/mono-nitro toluene in manufactured product. Purified TNT is used in ordnances to overcome such problems.

## **1.2 High Energy Alternatives to TNT and RDX/HMX**

R&D attempts are on to search replacement of TNT by alternative melt cast High Energy Materials (HEMs). Trinitroazetidine (TNAZ) and 1-Methyl-2, 4, 5-trinitroimidazole (MTNI) are widely reported as high energy substitutes of TNT in literature [7].

Researchers at Weapons Systems Division of ARDEC, USA have reported 1-Methyl-2,4, 5-trinitroimidazole (MTNI) as a promising candidate [8]. MTNI is a novel candidate owing to its melting point (82 °C) close to that of TNT and higher density of 1.78 g cm<sup>-3</sup>. Further its sensitivity is intermediate between RDX and TNT whereas performance is close to RDX. However, MTNI is still realized at lab scale and its production yet to be fully established [8].

TNAZ also offers energy level equivalent to that of RDX due to superior oxygen balance and heat of formation than that of TNT. In general, sensitivity levels of larger particle size ( $h_{50}$  29 cm) of TNAZ are comparable with those of HMX ( $h_{50}$  28 cm) and RDX ( $h_{50}$  32 cm) while smaller particle sizes of TNAZ exhibit impact sensitiveness ( $h_{50}$  66 cm) similar to that of TNT ( $h_{50}$  98 cm) [9]. It is being investigated by researchers all over the globe due to unique combination of high power and low vulnerability.

TNAZ has relatively higher melting point (101 °C) compared to TNT (80.8 °C) unlike MTNI (82 °C). TNAZ exist in at least two polymorphic forms. During solidification polymorphs transitions leads to development of defects within the polycrystalline lattice and shrinkage to the extent of about 15% [9]. This leads to formation of porous charges of unacceptable quality.

Major concern regarding application of TNAZ as melt cast explosive is high degree of volatility as its vapor pressure is much higher than that of TNT [9]. High concentrations of vapors pose hazards during melt-cast process. Hazards assessment brings out that TNAZ renders composition more sensitive than TNT based composition. In order to obtain high quality melt cast charges, additives need to be incorporated to lower its melt temperature and reduce vapor pressure. Modification of crystal morphology is also an alternative approach. N-Methyl-4-nitroaniline (MNA) is reported as an effective additive to bring down both melting point and

vapor pressure resulting in improved charge quality with reduced porosity [7]. Reich et al [10] studied at Eglin AFB, a number of TNAZ compositions incorporating various additives. These researchers have evaluated physical, chemical and sensitivity properties of TNAZ compositions containing TNB (1,3,5-trinitrobenzene), TNT, MNA, DNA (2, 4-dinitroaniline) and CAB (cellulose acetatebutyrate). The results obtained by Reich et al [10] suggest that TNAZ combination with MNA/DNA could be useable melt-cast formulations. Charge density increased from 89.4% theoretical maximum density (TMD) for pure cast TNAZ to 97.7% TMD for a 90/10 TNAZ / MNA composition. Although these compositions reduce performance due to their lower energy potential, calculated performance is within 1-4 % of that of cast TNAZ due to higher TMD. TNAZ/MNA in 80/20 combination offer improved charge quality and reduced shock sensitivity.

Watt and Cliff [11] processed melt-cast RDX/TNAZ composition using existing equipment. These researchers reported that RDX/TNAZ (60:40) exhibit sensitivity levels similar to pentolite (PETN/TNT). However, RDX/TNAZ composition ARX-4007 delivered much higher VOD (8660 m/s) and detonation pressure (33 GPa) compared to corresponding RDX/TNT composition (7440 m/s and 29.5 GPa). These HEM engineers are of the opinion that TNAZ cannot be adopted as a TNT replacement in melt cast system due to its higher cost, long synthetic route with poor yield and higher sensitivity. TNAZ also leads to highly porous and cracked charges due to shrinkage and its higher volatility [11]. Explosive

characteristics of major melt cast high energy alternatives of TNT are listed in Table 1.4.

**Table 1.4: Characteristics of High energy Alternatives to TNT**

High energy melt cast explosive	Heat of formation $\Delta H_f$ (kJ/mol)	Melting point (°C)	Density (g/cm <sup>3</sup> )	VOD (m/s)	Detonation pressure (GPa)
MTNI [7]	-----	82	1.78	8800	35.58
TNAZ [7,12]	+2	101	1.84	8600	35.68
TNT [1,7]	-62.7	80.8	1.64	6950	18.90

R & D activities aimed at incorporation of more powerful HEMs as replacement of RDX and HMX in explosive compositions are also pursued. Hexanitrohexaazaisowurtzitane (HNIW), popularly known as CL-20 is fast emerging as powerful alternative of RDX/HMX. Major attributes of CL-20 are its higher heat formation due to strained structure and superior oxygen balance than RDX/HMX. Cage structure of the molecule also results in close packing of constituent atoms leading to higher density. The most powerful explosive of today is being manufactured at various levels in most of the countries. A CL-20 manufacturing facility (5000 lbs/year) has been established by Thiokol, USA. Continued efforts are on to economize its production cost [13]. Efforts are also on to minimize sensitivity of CL-20. CL-20 has been extensively evaluated as component of military/commercial products in pressed explosives [14-17]. CL-20 based plastic bonded explosives (PBXs) are reported to deliver 12-15% higher energy compared to corresponding HMX based formulation

with respect to VOD [13]. Characteristics of CL-20 based plastic bonded explosives along with corresponding HMX based PBXs are listed in Table 1.5.

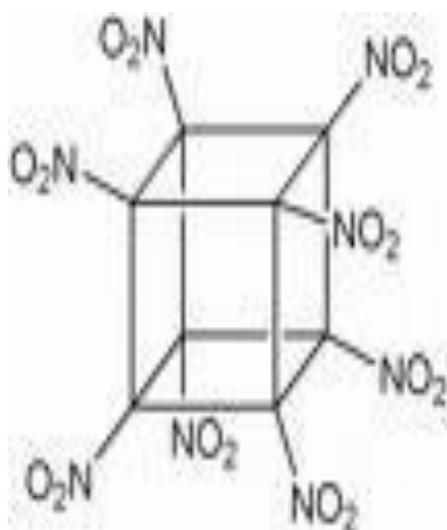
**Table 1.5: Characteristics of selected CL-20 based PBXs [13]**

Composition	Density (g/cm <sup>3</sup> )	VOD (m/s)
96%CL-20; 1% Hy Temp; 3% DOA	1.901	9018
96%HMX; 1% Hy Temp; 3% DOA	1.792	8748
66.8-72.1% CL-20; HTPB	1.648 - 1.710	8.325 - 8.470
66.8-72.1% HMX; HTPB	1.575 - 1.618	8.030 - 8.107
LX-19: 95% CL-20; estane	1.959	9440
LX-14: 95% HMX; estane	1.835	8790

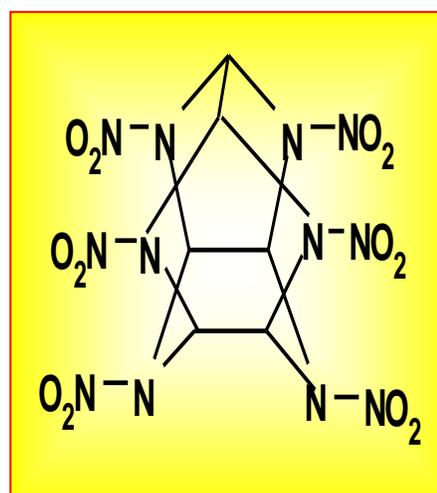
Thiboutot et al [18] have reported that CL-20 based melt cast compositions are not promising due to rapid polymorphic transition of  $\epsilon$ -polymorph of CL-20 to a less dense and marginally more sensitive  $\beta$ -polymorph in molten TNT.

Octanitrocubane (ONC) is considered the most powerful HEM of tomorrow for applications as explosive. Search is on for viable methods of its synthesis at pilot scale. Some of the R&D experts are of the opinion that high sensitivity of ONC will limit the scope of its application. Heptanitrocubane is being proposed as the molecule of interest [8]. Polynitrogens have evinced interest as viable HEMs of future on the basis of theoretical quantum mechanical calculations. Although polynitrogen

were considered as nonviable,  $N_5^+$  could be isolated in the form of salt ( $N_5^+AsF_6^-$ ) [19].  $N_8$  is considered a realizable polynitrogen by combining  $N_5^+$  and  $N_3^-$  due to its corollary with ONC. It is suggested that  $N_5^-$  has transient existence and can interact with  $N_5^+$  leading to formation of  $N_{10}$ . Manna [20] has reported that it may be possible to subject  $N_{10}$  molecules to ultra high pressure induced process leading to joining of six of its molecules into Buckminster fullerene configuration. Characteristics of Polynitrogen compound vs ONC & CL-20 are listed in Table 1.6 [8].



Octanitrocubane(ONC)



Hexanitrohexaazaisowurtzitane (CL-20)



**Buckminster fullerene configuration of N<sub>60</sub>**

**Table 1.6: Characteristics of Polynitrogen compounds vs  
ONC & CL-20**

<b>Compound</b>	<b>Density (g/cm<sup>3</sup>)</b>	<b>Heat of formation (kJ/mol)</b>	<b>VOD (m/s)</b>	<b>Detonation Pressure (GPa)</b>
N <sub>4</sub>	1.752	1123.16	13240	77.02
N <sub>5</sub>	1.850	1463	12510	73.95
N <sub>6</sub>	1.974	1444.52	14040	93.32
N <sub>8</sub>	2.15	1700	14860	108.39
N <sub>10</sub>	2.21	1978.81	12080	58.05
N <sub>12</sub>	2.28	2423.56	12530	64.07
N <sub>60</sub>	2.67	2282.28	17310	196.0
ONC	2.10	464	10100	50.0
CL-20	2.04	419	9400	41.9

### **1.3 Need of Low Vulnerable Explosives (LOVEX)**

Catastrophic damage suffered by Armed forces and civilians in proximity of site of explosion due to inadvertent detonation of ammunitions /warheads in depots/cargo have propelled HEM experts effort towards low vulnerable explosives (LOVEX).

Halifax explosion in Canada occurred during December 1917 remains world's most severe manmade explosion. It is reported to occur due to accidental collision of French Cargo Ship loaded with wartime explosives to a Norwegian Ship at Halifax Harbour. About 2000 person were killed and 9,000 people were injured during this incidence (fig.1.1). Exposure of energetic materials to combined effect of heat, shock and impact might have led to detonation which further propagated due to sympathetic reactions.

A catastrophic explosion of freighter SS fort Stikine carrying a mixed cargo at Mumbai during 1944 is also reported. Cargo of the ship contained about 1,395 tons of explosive including torpedoes, mines, shells and munitions. The accident led to death of about 1300 persons and injury to more than 2500 human beings (fig. 1.2).

Another accident in Staffordshire during 1944 caused death of more than 50 persons at RAF, UK underground storage. It involved explosion of about 4,000 tones of ordnance mainly comprising high explosive (HE) filled bombs and 500 million rifle ammunition rounds (fig.

1.3). About 120 m deep and 1,200 m dia crater is still visible to the west of Hanbury Hill.

Recently, about 100 containers of explosives seized by the United States Navy from a Russian owned vessel in the Red Sea and stored for 2½ year in open at Cyprus Naval Base exploded during 2009 leading to death of 12 persons and injury to 62 persons. Chemical reactions due to long exposure of explosive to environment are considered possible cause of heat buildup in the explosive leading to self detonation.

In India, explosion in INS Sindhurakshak during Aug 2013 led to demise of 18 Indian Navy sailors. An internal fire in the forward compartment of submarine storing ordnance is attributed to near-simultaneous explosions of explosive stores (fig. 1.3).



**Fig. 1.1: Explosion on French cargo Ship**



**Fig. 1.2: Explosion on freighter SS Fort Stikine Ship**



**Fig. 1.3: Explosion on INS Sindhurakshak**

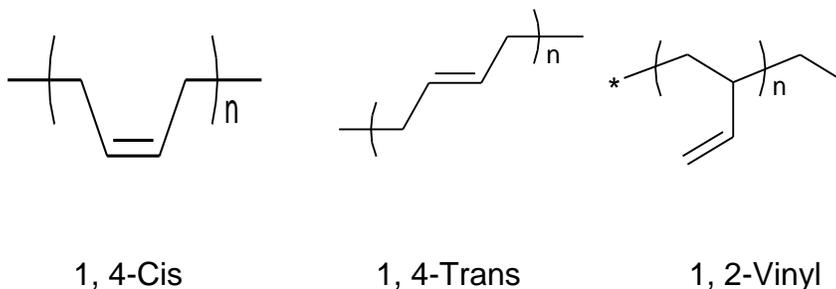
## **1.4 Approach to formulate low vulnerable explosive (LOVEX) compositions**

### **1.4.1 Plastic bonded explosives (PBXs)**

One of the approaches to realize LOVEX is to formulate PBXs comprising HE particulates dispersed in a polymeric binder. PBXs have advantage of improved thermal stability, insensitivity characteristics and superior mechanical strength compared to TNT based formulations due to polymeric matrix continuum. Polymer matrix offers a means to dissipate energy delivered by stimuli because of flexibility of polymer chain and high load bearing capability. A wide variety of polymers make it possible to tailor physical and explosive properties of PBXs to meet the desired operational requirements. Surfactants and processing aids enable to decrease proportion of binder without penalty on processibility and mechanical properties of compositions. The most promising polymer candidates for PBXs are polybutadienes, namely polybutadiene acrylonitrile (PBAN), carboxy Terminated polybutadiene (CTPB) and hydroxyl terminated polybutadiene (HTPB).

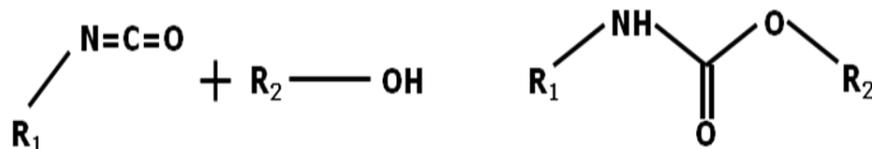
HTPB is preferred choice [21] for PBXs due to excellent heat resistance, high solid loading capacity (upto 87%) for HEMs leading to higher performance, high mechanical strength with improved structural integrity, low glass transition temperature (-80 °C) enabling flexibility even at sub ambient temperatures and clean curing reactions with curatives as well as negligible volume change post curing.

HTPB exists in 3 basic configuration viz. cis, trans and 1, 2-vinyl. Cis configuration with bending of successive C-C chain offering elongation whereas trans configuration with straight successive C-C chain segment resulting in straight and stiffened rod like structure offers high tensile strength to polymer chain.



In practice, all the three configurations are present in the manufactured product. Microstructure of HTPB has remarkable effect on the mechanical properties of cured explosive. An ideal HTPB should have trans: cis: vinyl in the ratio 55:25:20 for desirable mechanical property of composition. Vinyl content leads to increase in viscosity of uncured composition because of presence of pendant vinyl group which prevents the molecular slippage restricting the flow. It also reduces the load bearing capability of HTPB.

Generally isocyanate like Toluene diisocyanate (TDI), Hexa methylene diisocyanate (HMDI) and Isophorne di isocyanate (IPDI) are used as curative for HTPB in combination with catalyst like dibutyltin dilaurate (DBTDL) to adjust the pot life.



### Curing reaction

Non-aluminized and aluminized PBX compositions based on HTPB as a binder are widely reported in literature. R&D work has been carried out on non aluminized RDX/HMX based compositions as replacement of conventional Hexolites and Octol [22-25]. Gharia et al [26] have reported PBX compositions incorporating 80-88% RDX/HMX in HTPB matrix, same are given in Table 1.7. These researchers have found superior sensitivity characteristics of the PBXs over Composition B/Octol. They inferred that VOD of RDX/HMX-HTPB PBXs increases with increase in explosive loading. VOD of the compositions reported by these researchers ranged 7850-8330 m/s and 8100-8600 m/s for RDX and HMX based compositions respectively. Non aluminized cast cure composition ROWANEX-1100 is reported to be used for 105 and 155 mm projectile [27-28].

Aluminized RDX/HTPB based PBXs find wide application major application in ship/submarine borne torpedoes. The work on aluminized PBXs [4] is summarized in recently published review (Table 1.8 and 1.9). These classes of PBX compositions are reported to be inducted as the main charge fills in anti-ship Penguin missile, Hellfire missile and penetrator bombs [4]. Aluminized HMX PBX compositions offering superior density and velocity of detonation, compared to aluminized RDX

based compositions, are also well studied. Kumar et al [29] have evaluated performance characteristics of various aluminized PBX formulation with RDX/HTPB (85/15) composition as reference. Explosive bulge tests (EBTs) bring out that aluminized PBXs result in higher depth of bulge (30-35 mm) compared to reference non-aluminized composition 85/15 RDX/HTPB (28.2 mm). These researchers inferred that aluminized PBX-25 (RDX/Al/HTPB: 60/25/15) was most promising PBX formulation to replace HBX-3 (RDX/TNT/Al/Micro-crystalline Wax: 31.3/29/34.8/4.9) for underwater applications [29].

**Table 1.7: Composition and Characteristics of RDX/HMX-HTPB PBX Compositions**

<b>PBX Composition</b>	<b>Impact Sensitivity (h<sub>50</sub> cm)</b>	<b>Friction Sensitivity (kg)</b>	<b>Density (g/cm<sup>3</sup>)</b>	<b>VOD (m/s)</b>
RDX/HTPB (80/20)	142	>36.0	1.49	7850
RDX/HTPB (88/16)	100	32.4	1.60	8330
Composition B (RDX/TNT 60/40)	95	24.0	1.68	7500
HMX/HTPB (80/20)	130	36.0	1.58	8100
HMX/HTPB (88/16)	102	28.4	1.67	8600
Octol (HMX/TNT 70/30)	61	16.8	1.75	8200

**Table 1.8: Composition and Characteristics of Aluminized RDX based castable PBX Compositions**

<b>Nomenclature</b>	<b>RDX/Al/HTPB composition</b>	<b>Density (g/cm<sup>3</sup>)</b>	<b>VOD (m/s)</b>
HXA-177	67/15/18	1.60	7580
KS-22a	67/18/15	1.64	7400
PBXN-109	64/20/16	1.65	7200
HXA-171	52/30/18	1.67	7200
HXA-172	42/40/18	1.72	7050
HXA-173	32/50/18	1.77	6550

**Table 1.9: Composition and Characteristics of Aluminized HMX based Castable PBX Compositions**

<b>Nomenclature</b>	<b>HMX/Al/HTPB composition</b>	<b>Density (g/cm<sup>3</sup>)</b>	<b>VOD (m/s)</b>
PBXW-114	78/10/12	1.72	8230
PBXI-1	74/10/16	1.67	7750
PBXI-3	64/20/16	1.72	7450
CD-04	68/20/12	1.73	7780
KS-33D	80/10/10	1.75	8000
PBXN-113 PBXIH-135	45/35/20	1.68	6980

Nath et al [30] reported RDX/HTPB based PBX in the form of flexible sheet explosives offering superior density and VOD with relatively lower shock sensitivity compared to crepe rubber (CR), ethyl vinyl acetate (EVA), and estane-based composition. These compositions are potential candidates for ERA application (Table 1.10).

**Table 1.10: Sensitivity and performance parameters of thermoplastic elastomers (TPE) based PBXs in the form of sheet explosives**

PBX (Sheet) Composition	Sensitivity to various stimuli			Density (g/cm <sup>3</sup> )	VOD (m/s)
	Impact (h <sub>50</sub> cm)	Friction (kg)	Shock (Gpa)		
RDX/CR 80: 20	87	36	8.40	1.13	5861
RDX/EVA 80 : 20	85	36	6.83	1.28	6500
RDX/Estane 80: 20	82	36	7.88	1.20	6290
RDX/HTPB 85: 15	75	36	18.0	1.43	7200

CR: Crepe rubber, EVA: Ethyl vinyl acetate,

Estane: Thermoplastic polyurethane

#### **1.4.2 Low vulnerable Insensitive HEM<sub>s</sub> as alternate to TNT/RDX/HMX**

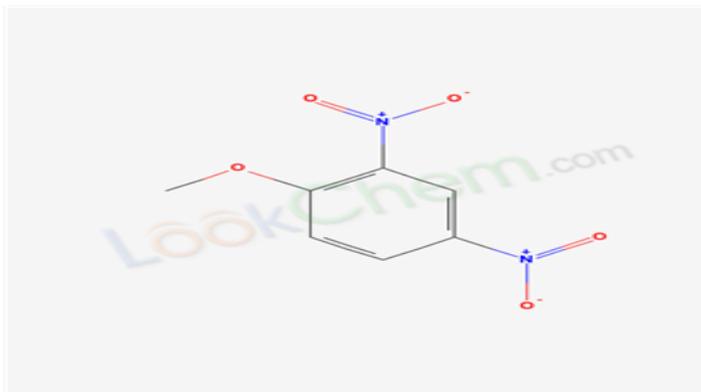
Despite above mentioned advantages of PBXs, melt cast compositions are still being used for wide range of missile warheads and ammunition in large quantum, particularly due to economical cost of production. Moreover, it is difficult to demilitarize cast cure PBXs filled ordnance by conventional means involving boil out of the explosive filling due to presence of cross links.

In order to mitigate hazards of melt cast explosives, inherently low vulnerable/insensitive HEMs offer an attractive approach adoptable for mass production of low vulnerable ammunition/warhead fillings at

economical cost using existing production facilities for melt cast compositions.

In this context, 1,1-diamino-2,2-dinitroethene (FOX-7), 3-Nitro-1,2,4-triazol-5-one (NTO) and 1,3,5-triamino-2,4,6-trinitrobenzene (TATB) have emerged as potential contenders for replacement of RDX/HMX and 2,4-Dinitroanisole (DNAN) is being explored as low vulnerable melt cast replacement of TNT.

Although DNAN delivered lower VOD (5600 m/s) and detonation pressure (7.02 GPa) compared to TNT, it has evinced interest due to categorization as class 4.1 flammable solid unlike TNT [7]. Melting point of DNAN is relatively higher (94-96 °C) compared to TNT (78-81 °C). However, it can be depressed to 78.6 °C by incorporation of N-methyl-4-nitroaniline (MNA) as additive [31].



### **2, 4-Dinitro anisole (DNAN)**

Initial work on DNAN compositions was reported by ATK Thiokol under US Government contracts. DNAN gained major attention with development of Picatinny Arsenal Explosive (PAX) formulations PAX-21 and PAX-25 followed by reports on PAX-33 and PAX-34. PAX-33 and

PAX-34 were originally developed by BAE Systems with nomenclature Ordnance Systems Explosive (OSX) formulations OSX-1 and OSX-3 [32, 33]. PAX-21 (RDX 36%, DNAN 34%, AP 30% & N-Methyl nitroaniline  $\leq$  1%) having lower shock sensitivity than composition B is being employed in munitions like 60 mm Mortar M720A1 shell [31].

Doll et al [34] patented DNAN based melt cast compositions. Explosive performance of compositions developed by these researchers is comparable to TNT based compositions. These compositions were found less sensitive to impact, shock and thermal stimuli rendering transportation regulations less stringent than for TNT compositions. Samuels [35] has reported advantage of much less exudation of DNAN (0.068%) compared to TNT (0.67%). Spycerelle et al [36] reported issues regarding irreversible growth of DNAN up to 15% after repeated thermal cycling.

Davies and Provatas [31] determined shock sensitivity (Large Scale Gap Test) and performance parameters of DNAN/DNAN based formulation ARX-4027 (Table 1.11). They have reported two variants of composition ARX-4027, one utilizing Type 1 Class 1 Reduced sensitivity RDX (RS-RDX) namely **ARX-4027 m<sub>1</sub>** and another **ARX-4027 m<sub>2</sub>** comprising of Type 2 Class 1 Dyno RDX. These researchers have found that insensitiveness of RS-RDX is not retained in the formulations.

**Table 1.11: Composition and Characteristics of DNAN and  
DNAN Based melt cast Compositions**

Compound/ Composition	Shock sensitivity (GPa)	VOD (m/s)		Detonation Pressure P <sub>CJ</sub> (GPa)	
		Calculated	Experimental	Calculated	Experimental
DNAN	7.02	5344	-----	9.51	-----
TNT	3.51	-----	-----	-----	-----
ARX-4027m <sub>2</sub> RDX/DNAN/MNA (60/39.75/0.25)	2.62	7296	7398	20.94	22.47
ARX-4027m <sub>1</sub> RDX/DNAN/MNA (60/39.75/0.25)	2.24	7296	7356	20.94	21.64
Comp B RDX/TNT (60/40)	2.69	7630	7843	24.77	24.55

In USA a family of melt-cast DNAN based explosives containing RDX or HMX, nitroguanidine (NQ), ammonium perchlorate (AP), NTO and aluminum powder has been developed under the name of Insensitive Military Explosive Composition (IMX). IMX-104 is being evaluated as a replacement for composition B in mortar systems. Army qualified DNAN based formulations reported by Philip Samuels [35] are inducted into services (Table 1.12).

**Table 1.12: US Army qualified DNAN based formulations**

<b>Nomenclature</b>	<b>Components</b>	<b>Application</b>
PAX-21	DNAN, RDX, AP	60 mm M720A1 Mortars
PAX-41	DNAN, RDX	Spider Grenade
PAX-48	DNAN, HMX, NTO	120mm IM-HE-T Round
IMX-101	DNAN, NTO, NQ	M795 IM & M1 IM artillery
IMX-104	DNAN, NTO, RDX	60/81/120mm mortar

Insensitive/low sensitive explosive molecules like Hexanitrostilbene (HNS), TATB, FOX-7 and NTO have evinced interest as replacement of RDX/HMX for LOVEX/Insensitive Munitions during past two decades.

HNS is a heat resistant insensitive explosive. Its higher thermal stability and insensitivity may be attributed to extended conjugation in the molecule. Despite its attractive insensitivity characteristics, HNS did not find major application in main explosive filling due to low energy potential. Currently, its application is reported mainly as a booster explosive, particularly in stage separation systems for space vehicles and for conduct of seismic experiments on the moon [37].

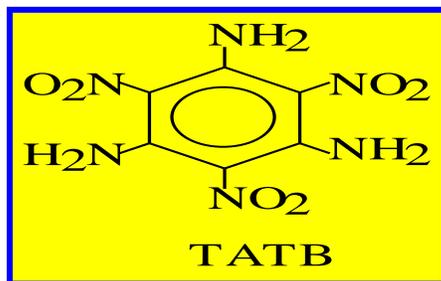
TATB is extremely insensitive to mechanical/shock/thermal stimuli with reasonable performance potential. Its delivered VOD is intermediate between TNT and RDX. TATB is often referred as thermally stable explosive owing to its much higher decomposition temperature compared to other HEMs. Its high degree of insensitivity is attributed to unique structural feature including elongated C – C bonds in the benzene ring, very short C – N bond involving amino substituent in combination with six

furcated hydrogen bonds. There are evidences of strong inter - and intra - molecular hydrogen bonds in TATB [38] leading to planar  $\pi$ -stacked structure like graphite [39]. Its application is predominant in system requiring extreme safety such as airborne nuclear weapons [40, 41] to avoid accidental detonation during aerodynamic heating and accident such as an airplane crash or rocket misfiring. Billon and Parry [42] have reported melt cast insensitive high explosives TATB/TNT (50:50) and TATB/TNT/Al (40:40:20) composition. However details on such composition are not revealed. TATB is widely reported as component of pressed PBX formulations including PBX-9502 (TATB/Kel-F chloro trifluoroethylene polymer 95:5) [42], LX-17-0 and PBX-9503 [43].

Singh et al [44] have reported series of compositions based on TATB/HMX/Viton. These researchers observed an increase in VOD from 7.4 km/s to 8.24 km/s on increase in HMX content from 10% to 80% by weight with increase in sensitivity towards impact/friction. They have concluded that favorable combination of TATB and HMX offer optimized level of insensitivity and performance. Some of these PBXs compositions may be considered as a potential replacement for conventional explosives (cast and press) [44].

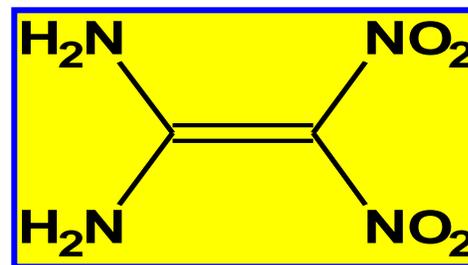
Research group in HEMRL [45] has evaluated TATB as part replacement of RDX in HTPB based plastic bonded sheet explosives (Table 1.13). Part replacement of RDX by TATB led to reduction in

vulnerability of the composition to shock stimuli without much penalty on energetic in terms of VOD.



1, 3, 5-triamino-2, 4, 6 – trinitrobenzene

**(TATB)**



1, 1-diamino-2, 2 dinitroethene

**(FOX-7 or DADNE)**

**Table 1.13: Sensitivity and performance parameters of TATB based PBXs in the form of sheet explosive**

PBX (Sheet) Composition	Sensitivity to various stimuli			VOD (m/s)
	Impact (h <sub>50</sub> cm)	Friction (kg)	Shock (GPa)	
RDX/HTPB (85:15)	75	36	18.0	7200
RDX/TATB/HTPB (75:10:15)	80	36	20.0	7150
RDX/TATB/HTPB (70:15:15)	87	36	22.9	7120
RDX/TATB/HTPB (65:20:15)	99	36	29.2	7100

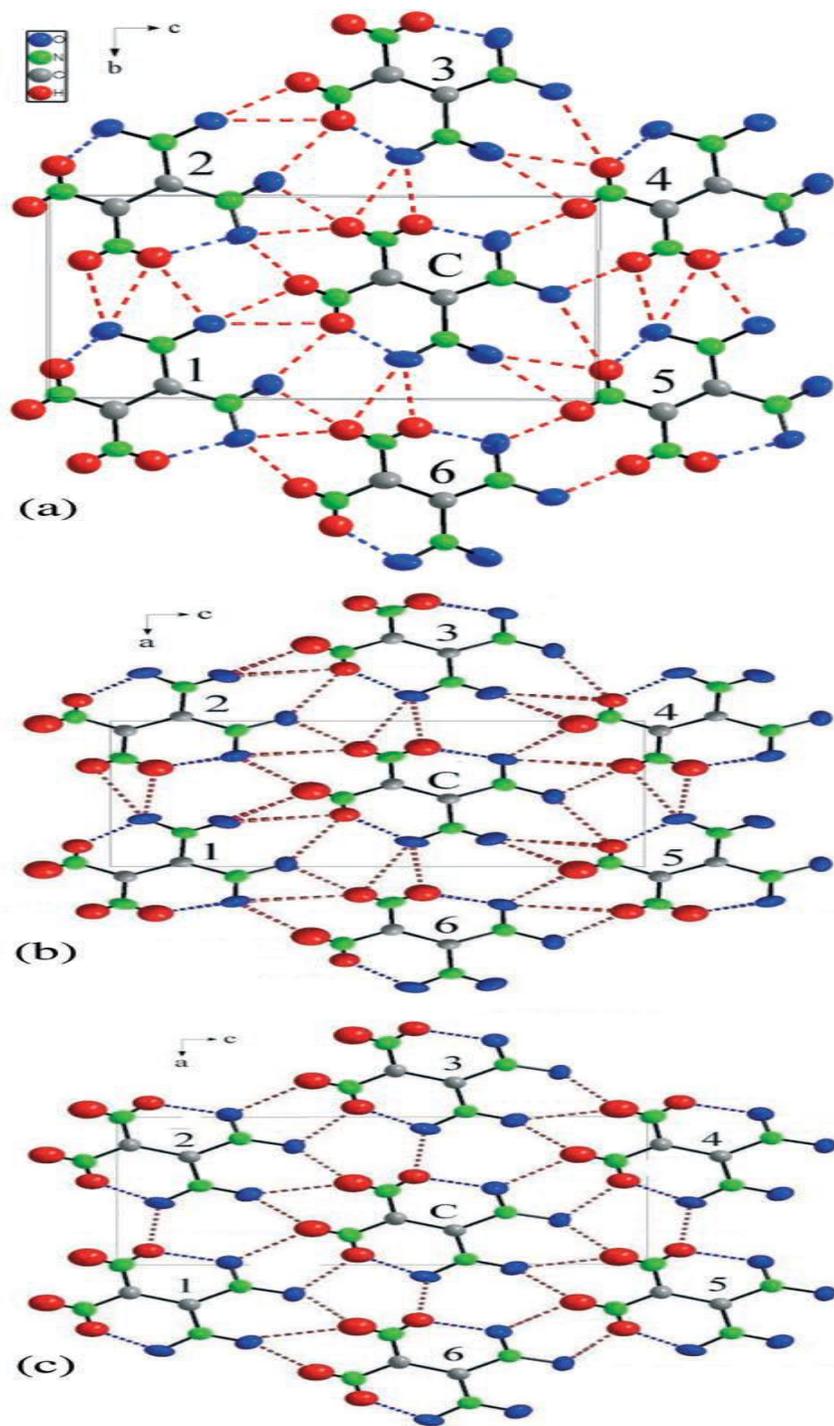
A large quantum of work is being carried out on evaluation of 1,1-diamino-2,2-dinitroethene (FOX-7 or DADNE) as component of explosive composition since its synthesis in late 1990's due to combination of lower sensitivity with performance comparable to RDX [46, 47]. FOX-7 has

molecular stoichiometry similar to RDX/HMX and generates more or less similar amount of major gaseous decomposition products (CO, N<sub>2</sub> and H<sub>2</sub>O). The reported activation energy for FOX-7 is higher ( $E_a = 58$  kcal/mol) than that of RDX/HMX ( $E_a = 40/35$  kcal/mol) favoring FOX-7 as potential insensitive explosive [12]. FOX-7 is being processed at pilot plant scale [48-52]. Studies on its characterization [53-54] and performance evaluation are widely reported in literature [55-57].

Lochert [53] reported significantly less sensitivity of FOX-7 compared to RDX towards impact as well as friction stimuli and compatibility with TNT in melt cast compositions. He has reported marginally higher velocity of detonation and detonation pressure for FOX-7 compositions than corresponding RDX compositions [53]. Dorsett [58] used first principles quantum chemical calculations to predict the initial steps of decomposition of FOX-7. He has reported that possible mechanisms for initiation of reaction in solid FOX-7 include (a) intra- or intermolecular hydrogen transfer, (b) nitro-nitrite isomerisation and (c) C-nitro bond cleavage.

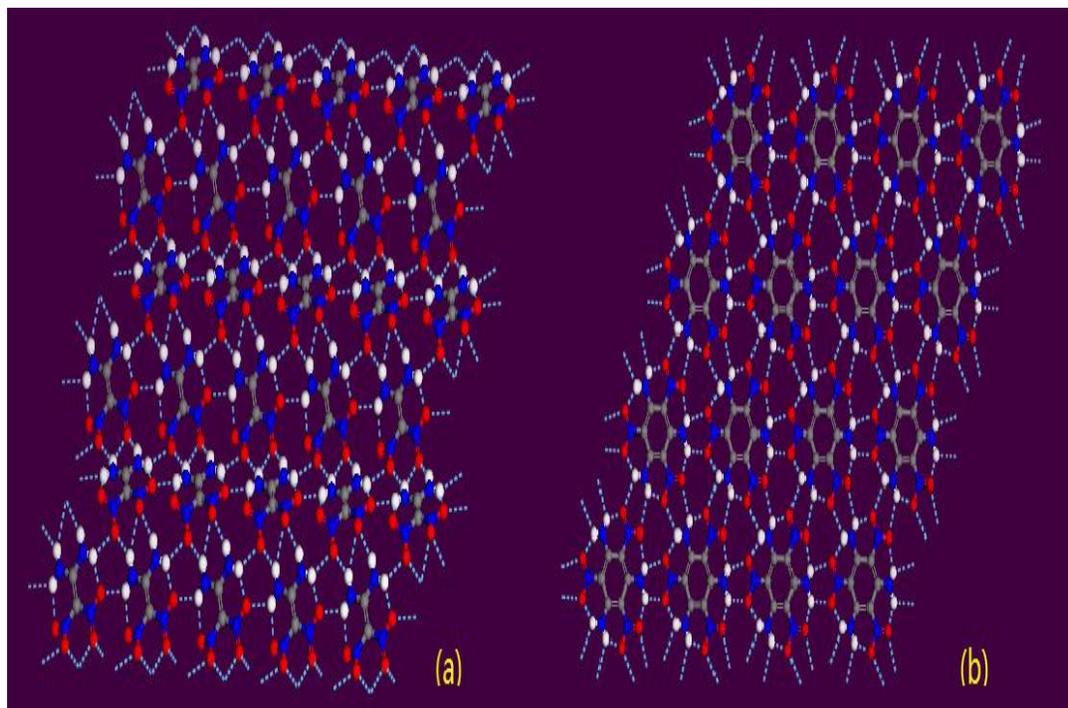
Crawford et al [59] reported FOX-7 exists in trimorphic form in solid state. The  $\alpha$ -phase is stable upto to 388 K, the  $\beta$ -phase exists in the temperature range of 388 to ~435 K and  $\gamma$ -phase ~435 K onwards upto thermal decomposition at 504 K. Crystal structure of the  $\alpha$ -phase has an infinite two dimensional wave-shaped layer structure consisting of FOX-7 molecules packed 'head-to-tail' within the layers. In  $\beta$  phase, dipolar

FOX-7 molecules pack as in  $\alpha$ -phase. These researchers reported participation of FOX-7 molecule in  $\alpha/\beta/\gamma$  phase in hydrogen bonding to six neighboring molecules (fig. 1.4). An average of 18 hydrogen bonds are reported between molecules 1 & 2 in  $\beta$  as well as  $\gamma$ -FOX-7 (fig. 1.4 a), with an overall average O...H distance of 248 & 243 pm respectively. Ten H-bonds involve nitro oxygen atom whereas eight H-bonds involve amino group atoms (fig. 1.4 b). In contrast, molecules in neighboring rows are aligned parallel to each other in  $\alpha$ -FOX-7 (fig. 1.4 c) and are shifted with respect to each other. In case of  $\alpha$ -FOX-7, 14 H-bonds are formed with participation of oxygen atoms of nitro groups in eight hydrogen bonds whereas amino hydrogen atoms participate in six H-bond, with an average O...H distance of 226 pm. Bemm and Ostmark [60] also reported stability of  $\alpha$ -FOX-7 under normal temperature conditions. They suggested that a combination of  $\pi$ -conjugation of  $\alpha$ -polymorphs with extensive intra/inter molecular hydrogen bonding is responsible for low sensitivity and high activation energy barrier observed for FOX-7. Role of strong inter- and intermolecular hydrogen bonds in stabilizing FOX-7 is also reported by Trzciński et al [61].



**Fig. 1.4:** Projections of seven molecules in layers of  $\gamma$ -FOX-7 [(a) 200 K],  $\beta$ -FOX-7 [423 K (b)] and  $\alpha$ -FOX-7 [373 K (c)]. The central molecule in each projection is marked "C" [59]

Wen et al [62] theoretically computed coefficient of thermal expansion (CTE) values for FOX-7 and TATB. These researchers predicted inter-layer van-der Waals forces exist along the b-axis in case of FOX-7 where as in case of TATB inter-layer van-der Waals forces contribute mainly along the c-axis. In case of wave like FOX-7 layer, hydrogen-bonding interactions contributes mainly along a-axis (fig. 1.5 a). In TATB intra-layer hydrogen-bonding interactions contribute almost equally along the a- and b-axis because of the planarity of the layers (fig. 1.5 b).

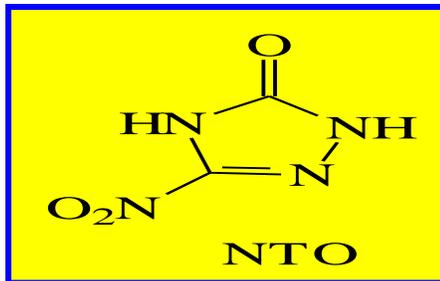


**Fig. 1.5: Hydrogen-bonding in the layers of a  $\pi$ -stacked structure of explosive crystals: (a) FOX-7 layer (b) TATB layer [62]**

Sensitivity characteristics of PBX formulation comprising FOX-7 with a poly Glyn binder has been reported by Karlsson et al [63]. The formulation does not detonate up to a diameter of 25 mm in large-scale detonation and small-scale slow cook-off tests. Ignition of the composition occurs around 220 °C on slow heating (3.3 °C/h) and it burns without damage to the container [63].

FOI Weapons and Protection Division of Swedish Defense Research Agency [64] developed a new formulation (FOF-5) based on FOX-7 and HMX, with theoretical performance equivalent to composition B. This composition was subjected to fast heating, slow heating and bullet impact tests. The response of a FOF-5 loaded 40 mm gun munition with HNS II-based fuze was Type IV (deflagration) in the fast heating, Type V/IV (fire/deflagration) in the slow heating, and Type V (fire) in the bullet impact tests. On the other hand, Composition B exhibited detonation response in all the tests [64]. HTPB based cast-cure PBXs incorporating FOX-7 as a part replacement of RDX have been reported to deliver higher VOD than control formulation RDX/HTPB [65].

3-Nitro-1, 2, 4-triazol-5-one (NTO) is another contender as promising low vulnerable replacement of RDX. In terms of detonation power, its performance is reported comparable to RDX, whereas it is far less sensitive than RDX like FOX-7 [66, 67]. Its insensitivity may be attributed to extensive hydrogen bonding between -NH groups and carbonyl as well as nitro groups [68].



### 3-Nitro-1, 2, 4-triazol-5-one (NTO)

Smith and Cliff [69] reported that NTO recrystallises from water as large, jagged, rod-like crystals, which tend to agglomerate posing problems during explosive formulation processing due to high viscosity of mix rendering it difficult to pour the composition in munition/warhead casing. These researchers reported that Spheroidal NTO can be formed by recrystallising crude NTO from low molecular weight alcohols such as methanol and ethanol. Rheological studies on cast cured PBXs are reported by various investigators [70].

NTO is reported to exist as two polymorphs [71].  $\alpha$ -NTO is the most prevalent stable polymorph. It is grown by slow cooling of a hot solution of NTO in various solvents (such as water), followed by refrigeration.  $\beta$ -NTO is formed by recrystallization from methanol or a mixed ethanol / dichloromethane solvent system. Crystals of  $\beta$ -polymorph are also obtained by cooling a hot aqueous solution of NTO. The  $\beta$  form decomposes within six months of formation [71].

Fung et al [72] observed Ordnance System Explosives (OSX) formulations, OSX-11 and OSX-12 based on NTO/DNAN/Al and

NTO/DNAN/RDX/Al respectively. These researchers studied processing parameters and sensitivity characteristics of the formulation. Potential of OSX-12 formulation is studied as replacement of PAX-28 formulation comprising of AP/DNAN/RDX/Al. These researchers have reported similar metal accelerating ability and IM properties of both the formulations viz. OSX-12 and PAX-28.

Trzcinski et al [73] studied NTO based melt cast formulations containing 40% TNT/DNAN, 20% of RDX and 40% of NTO. Studies undertaken by these researchers brought out lower detonation pressure and VOD of DNAN/RDX/NTO formulation than corresponding TNT based formulation however DNAN based formulations was found insensitive to impact (Table 1.14).

**Table 1.14: Impact Sensitivity and performance parameters of NTO/TNT-DNAN based melt cast formulation**

Explosive composition	Impact Sensitivity (J)	VOD (m/s)		Detonation Pressure $P_{CJ}$ (GPa)	
		Calculated	Measured	Calculated	Measured
TNT/RDX/NTO (40/20/40)	14	7453	7500 ± 100	22.18	23.1
DNAN/RDX/NTO (40/20/40)	25	7143	7190 ± 200	19.92	22.0

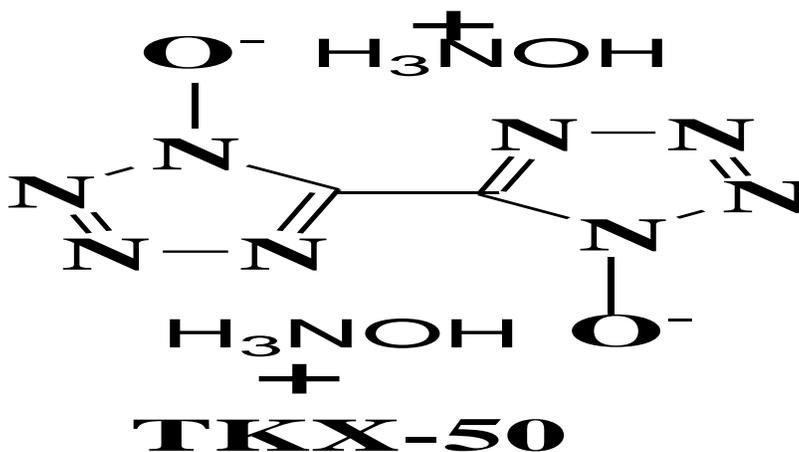
Spyckerlle et al [36] reported studies on non-aluminized and aluminized Ontalite (NTO/TNT) formulations. These researchers established that NTO/TNT in 50/50 combination has high potential for

application in ordnances. Effect of incorporation of RDX in Ontalites as additional tailoring factor was also studied. The energetics of NTO/TNT/RDX composition (55/35/10) are close to that of composition B, whereas 50/50 NTO/TNT (ARX-4002) delivered lower performance compared to composition B [69, 74].

Smith and Cliff [69, 74] reported extensive work on melt-cast NTO/TNT/Al compositions carried out under U.S. Air Force (USAF) programme. NTO based compositions AFX-644 and 645 delivered VOD almost close to that of the Tritonal standard, whereas their friction and impact sensitivities were found beyond the upper limit of the instrument. AFX-645 (air force explosive composition) contains a combination of Indramic-800 and Ganex WP-660 (98.5/1.5) in place of D<sub>2</sub> wax used in AFX-644 composition to overcome problem of exudation of D<sub>2</sub> wax (due to its lower melting point). IM testing of 5"/54 Naval projectile filled with ARX-4024 (NTO/TNT: 65/35) in their plugged logistical configuration was undertaken by Smith and Cliff [75]. The composition passed slow cook-off, liquid fuel fire, bullet impact and sympathetic reaction tests [75].

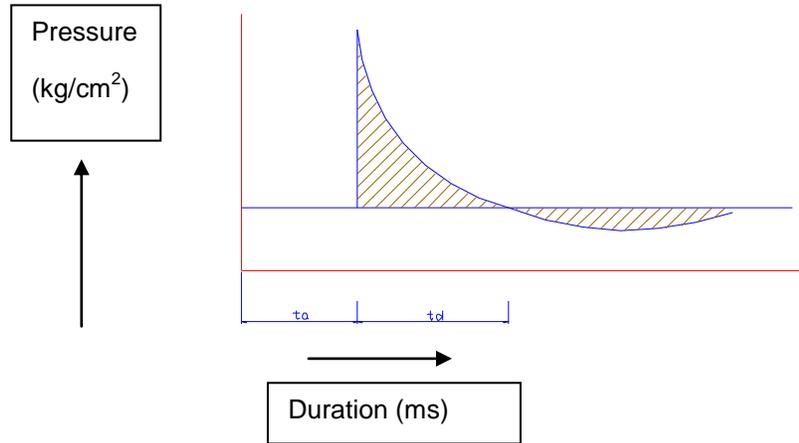
These results suggest that NTO based compositions are most likely candidates of Extremely Insensitive Detonating Substances (EIDS) and may meet the criteria of insensitive munitions of the HD 1.6 class for both storage and transportation.

During recent time, Dihydroxyl ammonium 5, 5'-bistetrazole-diolate (TKX-50) has been reported as one of the most promising ionic salts as a possible replacement for RDX. TKX-50 having performance (calculated VOD 9698 m/s) [76] comparable to that of CL-20 with much lower sensitivity level has high potential for application as secondary high explosive as well as a booster.



### 1.5 High density metal based metalized compositions

Parameters governing blast effect of explosive compositions are Peak over pressure (shock intensity), duration of blast wave and impulse (force-time product). Peak over pressure depends on the proportion of energetic ingredient in the composition whereas the duration and impulse have significant contribution from incorporated metal particulates. An ideal curve of Pressure v/s Duration (Blast curve) is depicted in fig. 1.6.



**Fig. 1.6: Ideal curve of Pressure v/s Duration**

As blast wave from an explosion travels outward, the volume of air behind the shock-front increases to such an extent that the initial volume of explosion products becomes negligible. At this stage, positive and negative phases depicted on pressure distance record of the explosive blast wave become almost equal in area. However, the positive pressure phase generally being more intense mainly contributes to the damage of the target.

In addition to aluminum, metals like molybdenum, zirconium, titanium and tungsten have also been investigated as component of metalized compositions particularly for achieving specific effects. However, fine zirconium and titanium powders being pyrophoric in nature pose hazards restricting their universal application. Among these metals zirconium and titanium find application in incendiary compositions for warheads/projectile. Owing to environmental concerns, tungsten is the preferred choice due to inert nature.

During recent times, tungsten based explosive compositions have evinced interest as candidate for ammunition used in low intensity conflicts (LIC) due to lethality at close range avoiding collateral damage. Tungsten powder is also capable of creating microscopic shrapnel at high temperature generated during explosion. R&D efforts are mainly focused on tungsten based Dense Inert Metal Explosive (DIME) realizing increased impulse with low Peak over Pressure (PoP) in near field to avoid collateral damage.

Tungsten finds application in shaped charges to enhance their penetration capability due to its higher density. Heavy metals like depleted uranium (DU) have also been investigated in shaped charges as a liner material. However, structural strength limitations are major issue with tungsten liners, particularly for large penetrator warheads. Further fabrication of tungsten liners and cases is cost-intensive. Moreover concentration of heavy metal at the walls of warheads degrades fragmentation performance.

Several researchers have reported high density explosive formulations incorporating tungsten powder. Weinland etal [77] reported improvement in impulsive effect of the explosive delivered to surrounding bodies on incorporation of tungsten in composition. Spencer etal [78] have patented a high density tungsten-loaded, castable explosive, comprising of 50-90 wt% tungsten powder, 3-40 wt% high energy explosive, 3-16 wt%

energetic binder and 2-10 wt% aluminum powder, as cost effective approach over tungsten case lined penetrator warheads.

Kato et al [79, 80] studied shaped charges comprising of an inner layer of tungsten incorporating high density PBX and an outer layer of high velocity PBX. The inner layer of PBX compositions incorporated 20/40/60 % of W powder. It was observed by these researchers that initial jet velocity and jet penetration velocity in the target plates were largely increased due to overdriven detonation in the tungsten-loaded high density explosive, thereby improving the performance of a shaped charge.

#### **1.6 Objective of the present study**

The literature scanned on explosive formulations bringing out the emerging trends in this area is briefly summarized in the preceding text. Low vulnerable explosive compositions are gaining importance for application in wide range of missile warheads/ammunitions due to hazard posed by conventional explosives because of probability of unplanned initiation resulting in catastrophic loss to human lives and material. Accidents resulting from unintentional initiation of explosive devices due to thermal/mechanical stimuli and sympathetic detonation are widely reported.

R&D work is mainly focused on realization of plastic bonded explosive with polymeric binder and incorporation of low vulnerable explosives as replacement of currently used HEMs. HEMs like FOX-7/NTO/TATB are being investigated as replacement of RDX/HMX. Despite

the extensive work, literature available on this class of composition is limited due to their strategic importance. Moreover, such compositions are studied to a limited extent for application in artillery/infantry ammunition and missile warheads, probably due to high cost factor of cast cure compositions with polymer matrix. Melt cast compositions offer an economical solution in this regards.

During this research work, highly promising HEM, FOX-7 having energetics close to that of RDX with relatively low vulnerability has been selected to generate detailed data. Other promising low vulnerable HEMs, namely NTO and TATB have also been investigated to generate data base. Aluminized variants of these compositions have also been studied from the point of view of their application in blast devices including warheads. DNAN has been selected as alternative to TNT to generate comparative data on performance and vulnerability. Potential of tungsten has been investigated as component of melt cast explosive composition from the point of view of exploring possibility of application in LIC warfare scenario demanding minimum collateral damage. In addition to evaluation of composition with respect to their vulnerability and performance level, thermal studies have been undertaken to understand effect of various HEMs on decomposition pattern and overall thermal stability of compositions studied during this research work.

The study is of immense value considering that information on melt cast low vulnerable compositions is almost non-existent despite their potential as economical filling of ammunition/warheads. Limited data is available only in case of NTO and to the some extent on DNAN based melt composition.

## **1.7 Scheme of the present study**

### **Chapter 1: Introduction**

This chapter deals with the importance of melt cast explosives in the present scenario of high explosives technology in defense sector. It includes overview of recent advances in melt cast explosive/plastic bonded explosive compositions developed all over the globe. Separate sections are devoted to new class of more powerful as well as low vulnerable explosives. This chapter also brings out objective of the present study in the end.

### **Chapter 2: Experimental**

This chapter describes broad specification of materials used in preparing melt cast high explosive formulations. Processing methods adopted for formulations/charges are given in brief. Series of Melt cast compositions formulated during research work are tabulated. Instrumental techniques/methods used during this study for determination of impact/friction/shock sensitivity, thermal stability, velocity of detonation and blast performance along with thermal analysis methods used to understand decomposition pattern are described and discussed in this

section. Method to compute Theoretical maximum density (TMD) of the formulations is also discussed. Method to determine detonability behavior of melt cast component DNAN is also elaborated.

### **Chapter 3: Results and Discussions**

This chapter presents data generated on FOX-7/NTO/TATB/RDX/HMX formulations based on melt cast explosives TNT/DNAN. This chapter also includes the results obtained for high density metal tungsten based metalized melt cast high explosive formulations in comparison to reference aluminized formulation. Thermal studies of prominent formulations using Differential Scanning Calorimetry (DSC) / Thermo Gravimetric Analysis (TGA) techniques also form part of this chapter. The chapter is divided into seven sub chapters as given below for systematic presentation of comprehensive data generated during this research work.

- 3.1 FOX-7/NTO/TATB-TNT compositions
- 3.2 Aluminized FOX-7/NTO-TNT compositions
- 3.3 Explosive characterization of 2, 4-dinitroanisole (DNAN)
- 3.4 RDX/HMX-DNAN compositions
- 3.5 FOX-7/NTO/TATB-DNAN compositions
- 3.6 Tungsten based aluminized melt cast high explosive compositions
- 3.7 Thermal characterization of melt cast compositions

#### **Chapter 4: General Discussions**

This chapter discusses major trends obtained for sensitivity parameters, performance parameters and thermal behavior of developed compositions. The results are analyzed and discussed on the basis of inherent characteristics of explosives. An attempt is made to explain data in the light of findings cited in literature.

#### **Chapter 5: Summary**

This chapter summarizes objective of the present research, experimentations, various observations and findings of the present study. References are included at the end of each chapter and thesis concludes with the list of publications of author.

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