CHAPTER – I

1. Introduction

Sheet explosives comprise of energetic materials / explosives dispersed in polymeric matrix. High energy materials (HEMs) provide the power/energy to accomplish objectives of system. Polymers provide continuum for dispersion of HEMs and play vital role in deciding structural integrity and flexibility as well as sensitivity of sheet explosive compositions. In addition to conventional explosives, insensitive / low sensitive explosives are also potential candidate for sheet explosives to realise low vulnerable formulations. The recent advancements in the science and technology of polymers have led to a major breakthrough in the technology of sheet explosives.

Development efforts for flexible sheet explosives commenced with the objective of realising flexible compositions as alternate to non-flexible explosive composition B based on RDX & TNT. Plastic bonded explosive compositions amenable to calendaring process to obtain sheet in required form are the material of choice. Sheet explosive compositions are tailored depending on need of explosive power, mechanical properties and sensitivity. These properties depend on the particle size of explosive, nature and proportion of binder/plasticizers.

1.1 Sheet Explosives: Civil Application

Sheet explosives are the most versatile products finding application in both military and civil operations. Well known commercial sheet explosive products are Detasheet (Du pont, USA), Nipolit (German) and Metabel\(^1\). They are widely used for metal cutting and on-field/underwater demolition. Sheet explosives have also found extensive application in metal industries for explosive forming, sizing, welding and cladding operations. Use of explosive riveting in aircraft construction is well reported\(^2\). Explosive hardening of metal sheet can be achieved by detonating a thin layer of plastic sheet explosive in contact with the surface of the metal to be hardened. An improvement
of the order of 100% in yield strength and 40% for TS is reported by this technique. It has been found that explosive hardening can result in mechanical properties similar to those obtained by heat treatment and cold working at economical cost. It leads to greater ductility of sample than in case of heat treatment\(^3\).

During explosive welding, two metal surfaces are driven together by explosive forces leading to their joining as an outcome of their high velocity collision. Explosive welding has come a long way since it was reported on by Philipchuk\(^3\) in 1957. A considerable amount of pioneering work in the area of explosive welding was carried out by Pearson at Ordnance Test Station in China Lake (California)\(^4\)-\(^5\). The theory and mechanism of explosive bonding is well reported\(^6\)-\(^11\). The most important explosive parameter for welding is detonation velocity of explosive composition which determines the collision point velocity i.e. the velocity at which the contact length between the flyer plate and base plate increases. In general, low detonation velocity explosive is better suited for explosive welding.

![Fig. 1.1 Methods of producing Explosive Clads](image)
1.2 Sheet Explosive: Military Application

During recent times, sheet explosives have gained tremendous importance as component of Explosive Reactive Armour (ERA). ERA consisting of sandwiched sheet explosives offers effective protection to armoured vehicles including tanks against attack by projectiles and warheads based on shaped charge. It augments protection capability of tank armour.

Courtney-Green\textsuperscript{12} reported that tank armours are designed with variable thickness in different configurations depending up on threat perception, and generally at oblique angles to make direct attack difficult. Armour of higher thickness sloped at $60^0-70^0$ in frontal arc which is considered the most vulnerable area. The sloped frontal armour is often referred to as glacis armour. Its slope at $60^0$ angle effectively doubles the thickness of armour, thereby providing protection to the order of almost double of thickness of the armour. The glacis plates of the T-80 tank are reported to be about 200 mm thick with slope angle of $68^0$. It corresponds to path length of 534 mm for penetration of explosive jet during direct attack. The armour is relatively less thick and sloped to relatively less extent at other locations of tank due to less probability of direct attack. Generally, thickness of side armour is about 100 mm and that of top armour ~70 mm. The thickness of armour at underside / belly is about 20 mm (Figure 1.2). As explosive jet length of most of modern shaped charge warheads/projectiles exceeds 800 mm, ERA concept is used to provide additional protection to tank without much penalty on weight of Tank.
Vered\textsuperscript{13} reported evolution of ERA as protection system for Tanks/ Armour fighting vehicles (AFVs). The concept was developed by Rafael after the experiences of Israeli Defence Force (IDF) during 1973 war. Transformation from concept to tailor made design led to introduction of reactive armour, Blazer. It was retrofitted on most of the Israeli tank as add-on kit. The performance of Blazer was proved during Lebanon war of 1982. Israeli CENTURION tanks were fitted with Blazer blocks on glacis, around turret and mantelet to protect main armour. Practical experience with Blazer in real combat conditions was gained during Peace for Galilee operation in Lebanon of 1982.

\textbf{Fig. 1.3} CENTURION tank fitted with Blazer blocks\textsuperscript{13}
Warford\textsuperscript{14} reported, Blazer armour consists of a series of bricks, attached to tank by bolt & nut. He also brought out that each brick contains special plastic explosive sandwiched between two steel plates. R&D efforts were continued to overcome limitation of the initial product. The problem of detonation chain reaction causing sympathetic detonation of adjacent bricks on initiation of given brick by projectile. It raised concern of safety of supporting tanks of friendly forces fitted with reactive armour. Further, it was a challenging task to replace damaged/detonated reactive armour bricks in war field. Soviet Union undertook development of ERA to seek solutions, in phased manner. First phase of the armour upgrade programme commenced during early 80s and improved ERA was fitted on a T-72 M1 during 1984. The modified ERA consisted of “blanket” of non-metallic applique bolted to the turret roof. In subsequent armour upgrade programme simple cast steel plates were added to the turret front. T-55 tanks with upgraded ERA were deployed in Afghanistan war during 1986. This “horseshoe” armour of about 100 – 150 mm thickness was intended to defeat infantry antitank weapons. Modern Russian Main Battle Tank is fitted with the most advanced ERA.
1.3 Function of ERA

Shaped charge jet from Warhead detonates sheet explosive sandwiched between metal plates which in turn are driven in opposite direction. The upper plate moves away from the armour disrupting the tip of the jet whereas lower plate moves towards armour disrupting the remaining portion of the jet. The overall effect is consumption of much of the jet in overcoming continuously renewed surface of the two metal plates. Thereby, insufficient material is left out in the jet to penetrate into Tank armour. The action of ERA against shaped charges is shown in Fig. 1.6.

Degradation of shaped charge jet crucially depends on the degree of obliquity between line of attack and angle of the ERA plates. If the jet attacks the plates at an angle of 90°, it continues to pass...
through initially created holes in the plates in spite of their movement. Optimum oblique angle offers greater the volume of metal placed in the jets path\textsuperscript{16}. Degradation of a shaped charge jet at various angels of obliquity is illustrated in figure 1.7.

![Graph showing effect of obliquity on shaped charges jet disruption by ERA\textsuperscript{15}](image)

**Fig. 1.7** Effect of obliquity on shaped charges jet disruption by ERA\textsuperscript{15}

Probability of detonation of sheet explosive depends on explosive jet characteristics of shaped charge in term of $V^2D$ where $V$ is velocity of jet in m/s and $D$ is diameter of explosive jet in mm. It is imperative to select a sheet explosive depending on type of shaped charge to be defeated. The critical energy ($E_n$) required to initiate the sheet explosive\textsuperscript{15} can be computed by using formula $E_n = \frac{p^2t}{\rho_0U_s}$ where $p$ is shock pressure in kbar, $t$ is shock duration in $\mu$s, $\rho_0$ is density of the jet in g/cm$^3$ and $U_s$ is shock velocity in m/s.

A theoretical estimate of the velocity of metal plate on explosion of sheet explosive is of paramount importance in the field of explosive dynamics\textsuperscript{15}. Velocity of the metal plate accelerated by sandwiched sheet explosive considering a normal impact of one dimensional wave can be theoretically computed from Detonation Head Model, Gurney Model and Hydrodynamic Model. Out of these, first two approaches give final velocity whereas the last approach gives both the acceleration and final velocity of the plate. In all these approaches, it is assumed that the plate is incompressible and derives its momentum from collision of expanding detonation products. Yadav\textsuperscript{16} determined flyer plate velocity on detonation of PETN based sheet explosive of
dimension of 150x150x7 mm by using radiographic technique. He correlated velocity of flyer metal plate with explosive energy and charge to metal mass ratio (C/M). He compared theoretically computed velocity of flyer plate with experimentally determined values and found that it increases with C/M ratio as shown in Fig.1.8.

![Fig. 1.8 Comparison of theoretical and experimental flyer plate velocities at different C/M ratio](image)

1.4 Studies on ERA

Held\textsuperscript{17} evaluated ERA in three different configurations against precision shaped charges of 64, 96, 144 mm calibre and non-precision shaped charges of 200 mm calibre under different NATO-angles. The first configuration was designed with 40mm thick front plate, 5mm thick Datasheet explosive and 15mm thick rear RHA plate. The overall arrangement is shown in figure 1.9.
Fig. 1.9 Test result\textsuperscript{17} with shaped charges of deferent calibre against single ERA sandwich in configuration 1
In second configuration two ERA sandwiches were used. The first one with 35 mm front plate, 3 mm sheet explosive, 10 mm rear plate, and the second sandwich having 20 mm front plate, with thickness of explosive sheet and rear metal plate same as for the first ERA sandwich. The two sandwiches were separated by a 25 mm RHA plate at perpendicular air gap of 95 mm for second plate and 45 mm for first plate (Fig. 1.11).
In third configuration with two ERA sandwiches in side armour mode, first ERA comprised of 20 mm front plate, 3 mm sheet explosive layer and 5 mm rear plate. The only difference in the second sandwich was 10 mm thickness of rear plate. Both the ERA sandwiches were placed at gap of 15 mm. A 25 mm RHA plate was positioned at 34 mm perpendicular air gap distance (Fig.1.12).
Fig. 1.12 Test result\textsuperscript{17} of shaped charges of different calibre against the ERA in configuration 3

It was observed by Held\textsuperscript{17} that increase in shaped charge calibre up to 144 mm led to increase in extent of penetration. However 144 mm shaped charge and 200 mm non-precise shaped charge exhibited similar penetration level. Experiments on 96 mm calibre shaped charge brought out that reactive armour with single sandwich configuration have strong dependence on angle of attack with respect to protection level. It was observed that penetration level increases with decrease in angle of attack from 60° to 30° as depicted in the diagram below. An analysis of these results brought out that ERA with double sandwich is more effective compared to ERA with one sandwich.
Fig. 1.13 Line of sight penetrations in steel as a function of shaped charge diameter in three ERA arranged at 60° angle\textsuperscript{17}

Yadav et al\textsuperscript{18} studied shock sensitivity of RDX based sheet explosive with crape rubber binder conducting gap test and measured the attenuation of explosively generated shock in a right circular Al block of different thicknesses. He assessed critical thickness of block for detonation of sheet explosive and parameters of non-reactive shock wave initiation of sheet explosive with 50% probability. The experimental arrangement for the measurements is shown in Fig. 1.14. In first set of experiments a cylindrical donor charge of RDX/Wax of 30 mm diameter and 100 mm height, having density of 1.64 g/cm\textsuperscript{3} was used to obtained rate of attenuation of shock wave in the Al block of 2.785 g/cm\textsuperscript{3} density and 63 mm diameter with height varying from 10 to 44 mm.
Fig. 1.14 Experimental setup for measuring shock and free surface velocity in aluminium block

Fig. 1.15 Typical oscillogram showing the arrival of the wave at different probe locations of (time base 2 µs/div.)

In next set of experiments yadav et al determined, maximum height of Al block across which test sheet explosive of 1.28 gm/cm³ density and 6.5 mm thickness could be detonated with 50 % probability.
It was found that shock pressure of 11 kbar was required to initiate the test explosive.

**Fig. 1.16** Experimental setup for measuring shock initiation in sheet explosive

In third set of experiment depicted in Fig 1.17 was used to measure non-reactive shock wave in the sheet explosive to assess pressure of transmitted wave pressure required to initiate the sheet explosive of different thicknesses (4.25 - 10.75 mm).

**Fig. 1.17** Experimental setup for measurement of velocity of non-reactive shock wave in sheet explosive

15
These results indicate that the sheet explosive of 6.5 mm thickness detonates in all tests across barrier of thickness upto 38 mm whereas it was not detonated beyond 42 mm thickness of metal barrier in the given set up. Shock pressure of 47 kbar was determined across 40 mm thick Al block and can be considered threshold for non-reactive shock wave.

Asay et al\textsuperscript{19} studied the shock compression of DuPont Datasheet at low stress and determined non-reactive shock response of DuPont Datasheet up to a stress level of 3 GPa. PVDF stress-rate gages were used by these researchers and equilibrium/viscoplastic response were recorded with high-time-resolution.

Austing et al\textsuperscript{20} studied critical initiation energies of composition C4 (91% RDX and 9% Plasticizer) and commercially available sheet explosive Datasheet. Steel-covered C4 composition and Datasheet acceptor charges were shock initiated to detonation by the impact of explosively driven steel flyer plate across air gap during experiments.

\textbf{Fig. 1.18} Shock attenuation curve for aluminium\textsuperscript{18}
conducted by these researchers. Donor charges (Detasheet) imparting the velocity to the flyer plate was obtained from increments of sheet explosive of equal thickness by varying number of increments of the sheet explosives. A wide range of impact velocities and internal energies were determined experimentally and non initiation/initiation regimes of each acceptor explosive were bracketed. It was concluded by these researchers that critical initiation energy for composition C4 is 0.91 - 1.21 J/mm$^2$, and that for the sheet explosive is 0.95 - 1.29 J/mm$^2$.

**Fig. 1.19** Arrangement to determine the amount of donor charge required to shock initiate the acceptor charge by flyer plate impact across an air gap$^{20}$.

Golubev et al$^{21}$ determined nature of damage to test specimens with cupper coating on loading by explosion of sheet explosive charge. Fracture pattern of steel and cupper specimens with galvanic copper coating under explosion loading were studied to determine dependence of the critical negative pressure at initial fracture point on the pressure
Lee et al\textsuperscript{22} experimentally investigated possibility of enhancing detonation power of sheet explosives by electric energy input. During experiments conducted by Lee et al, a piece of 2mm thick sheet explosive was placed between two copper electrodes and electric energy of the order of 5 kJ was supplied to the detonating explosive from a capacitor bank. Energy deposited in the detonating explosive was estimated to be 3.2-4.3 kJ. An increase in detonation velocity by 2.7-3.2 \% on average and 8.2-10.4 \% locally was recorded during these studies. The increase occurred with a time lag of 10-18 ms after the electric energy input. It was suggested that the electric energy was supplied to the reaction zone in the form of heat and it took a short while for the heat energy to be transferred to the detonation front.

The explosive sheet contained in ERA is required to be insensitive against the attack by small arms / fragments from detonating artillery shells / sub munitions. Limited studies are carried out to understand phenomenon of detonation of a sheet explosive in ERA configuration on impact of KE projectile. Impact pressure on the sandwich (P) can be computed from impact velocity and its penetration velocity in the target by using the formula, \( P = 0.5 \rho_P (V_P - u)^2 \), where P is impact pressure, \( \rho_P \) is density of the projectile, \( V_P \) is impact velocity of the projectile, \( u \) is penetration velocity given by relationship \( V_P / (1+\gamma) \) where \( \gamma = \sqrt{\rho_t / \rho_P} \) (\( \rho_t \) refers to density of the target and \( \rho_P \) to density of the penetrator). Although ERA reacts on penetration by an Armour Piercing Fin Stabilized Discarding Sabot (APFSDS) projectile in much the same way as it acts on shaped charge jets, performance of APFSDS is degraded only marginally due to its much greater mass\textsuperscript{15}.

1.5 Sheet Explosive formulations:

All over the globe, sheet explosives are developed incorporating energetic materials, polymeric binders along with additives like
plasticizer with a wide range of mechanical properties, sensitivity and power (VOD) depending on application.

Penta erythritol tetranitrate (PETN) and cyclotrimethylene trinitramine (RDX) are widely reported as explosive components of sheet explosive formulations. Cyclotetramethylene tetranitramine (HMX) also finds application in some of the reported sheet explosive compositions.

Polymeric binders like poly-cis-isoprene (natural rubber/crepe rubber), poly-isobutalene (PIB), and co-polymer HyTemp have found application as binder in sheet explosive formulations. Nitrocellulose (NC) also finds application in many sheet explosives.

PETN: VOD: 8100 m/s
RDX: VOD: 8700 m/s
HMX: VOD: 9100 m/s

Natural rubber
Poly-isobutalene
Nitrocellulose

(Monomers of HyTemp)
The Detacord and Detaflex are the precursor of sheet explosive. Dupont introduced well known sheet explosive detasheet\textsuperscript{23} containing 85% PETN with elastomeric binder. It is reported to retain flexibility and explosive properties over a wide temperature range. In addition, it is safe to use and is completely water proof. Detasheet is available in two variants viz. Detasheet A containing 85% PETN and Datasheet C containing 63% PETN and 8% NC. Detasheet finds application in underwater demolition, seismic prospecting and metal cutting. Variant C is mainly used for military applications. Detasheet is also reported as component of ERA\textsuperscript{17}.

Wells\textsuperscript{24} reported a non-proprietary flexible sheet explosive EL-506C containing RDX as replacement for PETN based flexible sheet explosives developed by DuPont. HMX and RDX/HMX mix based sheet explosive have also been developed having explosive power equivalent or superior to flexible explosive EL-506C. A wide range of sheet explosive compositions based on a combination of RDX (Type B), HMX (grade II), citroflex A4 and dynamite grade nitrocellulose with additives like diphenyl amine (DPA) and pigments is reported in literature.

Walley\textsuperscript{25} developed a sheet explosive comprising of alternating layer of an explosive and a metal/plastic foil of a different thickness and density with a space forming material such as metal or plastic foam. It is found effective for initiating entire surface area of a geometrically shaped based charge leading to formation of a focussed detonation wave about a geometric centre.

Chen et al\textsuperscript{26} have described a large number of newly developed self-supporting sheet explosive composition. They have discussed effect of HEMs (RDX, TNT, NH\textsubscript{4}NO\textsubscript{3}) and binders on detonation velocity, impact sensitivity, friction sensitivity, explosion temperature and electro static sensitivity of the compositions. These researchers established an empirical formula for computing ultimate detonation velocity as function of sheet explosive composition thickness as well as molecular structure of the explosive component.
Minekawa et al\textsuperscript{27} developed a flexible explosive composition containing block copolymers. The invention pertains to composition consisting essentially of a cap sensitive high explosive compound such as nitric ester/nitramine which may be easily initiated under a released condition by the conventional detonator or an oxidizing agent along with a thermoplastic block copolymer. The block polymer consists of conjugated diolefin and monovinyl aromatic hydrocarbon segments. The composition may be formed into a sheet or strand. The shaped explosive with good flexibility has utility in explosive engineering of metals.

Park et al\textsuperscript{28} developed sheet explosive DXD-19 comprising PTEN and HyTemp binder with plasticizer. PETN is coated with inert plasticizer ATEC (acetyl triethyl citrate) for desensitisation before mixing operation. HyTemp 4454 a copolymer is obtained from ethyl acrylate and butyl acrylate monomers. Nitroplasticizer BDNPA/F was added as plasticizer with CAB (cellulose acetate butyrate) as reinforcing agent. DXD-19 is manufactured by solvent slurry method using dichloroethane (DCE) as solvent. DXD-19 has density of 1.52 g/cc and detonation velocity of 7210 m/s. It has impact sensitivity of 22.2 Joule and friction sensitivity of 28.6 kg with percentage elongation of 15.5\%. DXD-19 is thermally stable up to 145 °C with Tg of -57 °C. It finds application as deforming charge in direct energy warhead design.

![Extruded sheet explosive](image)

**Fig. 1.20** Extruded sheet explosive\textsuperscript{28}

Wagner et al\textsuperscript{29} reported low flammability cap sensitive
PETN/RDX based flexible explosive composition incorporating finally divided cap sensitive explosive in a flame resistant polymeric binder system along with a flame retardant material. RDX based composition contains Viton and Teflon as binder with Boric Acid as additive. PETN based sheet explosive also contains Viton and Teflon binder with zinc borate and hydrated alumina as additive. The VOD of RDX and PETN based composition are reported 6350 m/s and 5614 m/s respectively. These compositions exhibit markedly reduced flammability both in term of ignition resistance and burning rate.

Nippon Oils and Fats Co Ltd Japan\textsuperscript{30} developed NC-NG based sheet explosive having several projections on surface. Processing of sheet explosive involved suspension of 50 part NC in water mix along with 35 part nitroglycerine with 10 parts diethyl phthalate, 2.5 parts diphenyl amine and 2.5 parts organic Pb salt. The mix was dewatered and moulded to obtain sheet form.

Hopper et al\textsuperscript{31} reported composition comprising of a particulate explosives and plasticized binder for application in explosive metal-forming processes and demolition operations. The composition is found safe in handling and can be formed readily into any desired shape by rolling/extrusion/compression-moulding to obtain stripes/blocks/sheets.

Eurenco\textsuperscript{32} has reported PETN based flexible sheet explosives for civil and military application for demolition, breaching and cutting performance. The compositions known as FORMEX and SESAMAX contain 89 % PETN and 11 % natural rubber as binder.

An Indian Patent describes a PETN based sensitive sheet explosive with low VOD for application in cladding of metal plates\textsuperscript{33}. It consists of PETN and KNO\textsubscript{3} combination with crepe rubber as binder and zinc dithio carbamate as curing agent. The composition was rolled in the sheet form on a polished metal plate and cured at room temperature. The sheets were cut into convenient sizes and subjected to water leaching to remove potassium nitrate of composition in order to achieve low density and low VOD sheet explosive for metal cladding applications.
Compositions of well known sheet explosive are tabulated below.

**PETN based Sheet Explosives**

<table>
<thead>
<tr>
<th>Detasheet C, Dupont USA</th>
<th>% composition</th>
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</thead>
<tbody>
<tr>
<td>PETN</td>
<td>63.0</td>
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<tr>
<td>NC</td>
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<td>Plasticizer</td>
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<tr>
<th>Primasheet- 1000 (USA)</th>
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<tr>
<td>PETN</td>
<td>63.5</td>
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<tr>
<td>NC</td>
<td>8</td>
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<tr>
<td>Citroflex</td>
<td>28.4</td>
</tr>
<tr>
<td>C black, Fe₂O₃ &amp; DMNB</td>
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DMNB = 2,3 dimethyl 2,3 dinitrobutane

<table>
<thead>
<tr>
<th>EL 506, TYPE II</th>
<th>% composition</th>
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<tbody>
<tr>
<td>PETN</td>
<td>63.0</td>
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<tr>
<td>Citroflex A4</td>
<td>28.2</td>
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<tr>
<td>Dynamite grade NC</td>
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<tr>
<td>Olive-drab pigment</td>
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<table>
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<th>FORMEX/SESAMEX (EURENCO)</th>
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<td>PETN</td>
<td>89</td>
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<td>Binder (Natural Rubber)</td>
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<table>
<thead>
<tr>
<th>Sensitive Sheet Explosive with Low VOD</th>
<th>% composition</th>
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<tbody>
<tr>
<td>PETN</td>
<td>35</td>
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<tr>
<td>KNO₃</td>
<td>55</td>
</tr>
<tr>
<td>Crepe Rubber (CR)</td>
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<tr>
<td>Zinc Dithio Carbamate</td>
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</table>
## RDX based Sheet Explosive

### Flexible Sheet Explosive, USA (Composition 35) % composition

<table>
<thead>
<tr>
<th>Component</th>
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<tbody>
<tr>
<td>RDX</td>
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<tr>
<td>Nitrocellulose</td>
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<td>Citroflex A4</td>
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<td>Lampblack</td>
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<td>Crome Yellow Medium</td>
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<tr>
<td>DPA (Purified)</td>
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### Primasheet- 2000 (USA) % composition

<table>
<thead>
<tr>
<th>Component</th>
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<tbody>
<tr>
<td>RDX</td>
<td>63.5</td>
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<td>NC</td>
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<td>Citroflex</td>
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<td>C black, Fe$_2$O$_3$ &amp; DMNB</td>
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### C-4 Composition, USA % composition

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<tbody>
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<td>Poly isobutylene</td>
<td>2.1</td>
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<tr>
<td>Motor oil</td>
<td>1.6</td>
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<tr>
<td>Diethyl hexyl sebacate/adipate</td>
<td>5.3</td>
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<tr>
<td>DMNB</td>
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HMX based Sheet Explosive

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<tr>
<th>Flexible Sheet Explosive, USA (Composition 37)</th>
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<td>RDX</td>
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<td>HMX</td>
<td>29.6</td>
</tr>
<tr>
<td>Nitrocellulose</td>
<td>8.0</td>
</tr>
<tr>
<td>Citroflex A4</td>
<td>28.2</td>
</tr>
<tr>
<td>DPA</td>
<td>4.0</td>
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<tr>
<td>Pigment</td>
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<table>
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<tr>
<th>Flexible Sheet Explosive, USA (Composition 38)</th>
<th>% composition</th>
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<tbody>
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<td>HMX 655-61</td>
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<tr>
<td>Nitrocellulose</td>
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<tr>
<td>Citroflex A4</td>
<td>28.2</td>
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<tr>
<td>DPA</td>
<td>0.4</td>
</tr>
<tr>
<td>Pigment</td>
<td>0.8</td>
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</tbody>
</table>

1.6 Processing of Sheet Explosive:

Methods widely used for preparation of sheet explosive formulation are discussed below. Explosive up to 80-90% level can be incorporated in formulations by adopting these processing techniques.

(i) Solvent method: It involves swelling of cut pieces of calculated quantity of binders in selected solvent to obtain a uniform gel. The gel is transferred to sigma blade mixer and weighed quantity of explosive component is added in instalments. Steam/ hot water is passed into mixer jacket and mixing is continued for about 2-3 hr at elevated temperature. During mixing operation, part of the solvent is evaporated leading to formation of dough which is rolled between a pair of hot rollers to obtain sheet of desired dimensions.
(ii) **Processing with solvent free polymer de-polymerization technique:** This method offers a means of processing compositions based on viscous rubber by solvent-free process. It involves mixing of binder with wet explosive in a sigma mixer/masticator. During mixing process, most of the water gets separated from the explosive composition and residual water is squeezed out by rolling of mix at 40°C. The final product with water content of 1% can be shaped into plates or ribbons by means of calendaring accompanied with vulcanization at 80°C.

(iii) **Extrusion technique:** This method involves passing of softened explosive obtained as in method (i) and binder mix under pressure through a suitable die in order to produce a uniform product of desired cross-section at high production rate.

(iv) **Casting method with latex:** It involves mixing of liquid latex as water emulsion with 60% rubber content in a planetary mixer along with vulcanizer and an anti-aging agent. Subsequently, a calculated quantity of wet explosive is added to homogeneous liquid in planetary mixer and mixing operation is continued. The mix is poured on a Plaster of Paris plate which absorbs most of the water within one / two day. The dried composition is subjected to vulcanization at 60°C. It is followed by rolling at 60°C to remove remaining water as well as obtain desired dimension of sheet explosive. In this method about explosive powder up to 85 % level can only be loaded to liquid latex.

(v) **Cast-cured method:** In this method, calculated quantity of cast-cured HTPB along with processing aids is transferred to sigma blade mixer and uniform mix is obtained at 45-50°C. The calculated quantity of moisture free explosive is added in 26 instalments and mixing is continued for two hour at 45-50°C with RH control 50 to 55% level. Temperature of the mix is brought down to 25°C and calculated quantity of isocyanate curative is added followed by mixing for about 50-60 min to obtain uniform dough. The dough is allowed to semi-cure in trays under RH control. The semi-cured mass is rolled between rollers at ambient temperature to realize sheet explosive of desired dimension.
1.7 Emerging trends in Plastic Bonded Explosives:

According to literature scan, PETN and RDX are used in most of the sheet explosive compositions. HMX is also reported as explosive component of selected sheet explosive compositions. R&D advances made in the area of PBXs can have spin-off in the field of sheet explosives\textsuperscript{34}.

Among HEMs, potential of most powerful high explosive of today 2,4,6,8,10,12–hexanitro-2,4,6,8,10,12-hexaazaaisowurtzitane\textsuperscript{35} (CL-20) may be explored. Although it is more sensitive to impact and friction stimuli, it requiring special attention during processing of compositions in view of hazards, sensitivity of CL-20 to one-dimensional shock loading is reported to be similar to HMX\textsuperscript{36}.

![CL-20](image)

CL-20

VOD: 9400 m/s

Roux et al\textsuperscript{37} reported CL-20 based cast cure PBXs. The compositions containing CL-20 and HTPB in 91:9 ratio delivered VOD of the order of 8850 m/s with detonation pressure of 0.3448 Mbar. Friction/impact/shock sensitivity and overall vulnerability of the composition are reported to be comparable to HMX-Estane based pressed explosive LX-14 having VOD of the order of 8785 m/s. Simpson et al\textsuperscript{35} developed CL-20 based pressed formulations with Estane binder (Rx-39-AB) and EVA binder (PBXC-19).

A wide range of PBXs based on low vulnerable high explosives 3-Nitro-1,2,4-triazol-5-one (NTO) is reported in literature particularly for naval applications.
Powale et al.\textsuperscript{38} studied influence of different solvents and crystallization parameters to obtain low vulnerable NTO for application in insensitive explosives compositions. Thermally stable 1,3,5-triamino-2,4,6-trinitrobenzene (TATB) also find application in PBXs\textsuperscript{39}.

\begin{center}
\begin{tabular}{c|c}
NTO & TATB \\
VOD: 8100 m/s & VOD: 8000 m/s \\
\end{tabular}
\end{center}

1,1-Diamino-2,2-dinitroethene (FOX-7) is also emerging as powerful low vulnerable contender for melt cast compositions\textsuperscript{40}. Dihydroxylammonium 5,5'-bistetrazole-1,1'-diolate (TKX-50) is new entrant in class of low vulnerable explosives with high performance potential and can find application in future sheet explosives\textsuperscript{41}.

\begin{center}
\begin{tabular}{c|c}
FOX-7 & TKX-50 \\
VOD: 8800 m/s & VOD: 9700 \\
\end{tabular}
\end{center}

1.8 \textbf{Emerging trends: Polymeric Binders}

Among polymers, low molecular weight liquid poly-butadienes with terminal functional group, carboxyl terminated (CTPB) and hydroxyl terminated (HTPB) polybutadiene have found wide application in the area of propellants and PBXs\textsuperscript{42}. HTPB is a preferred choice due to clean curing reaction, stable urethane linkage formed by isocyanate
curative and superior fuel content\textsuperscript{43}. Application of HTPB can be extended to sheet explosives.

Radwan\textsuperscript{44} reported that 88\% RDX and 12\% HTPB based PBX displays enhanced insensitivity towards impact and thermal stimuli compared to RDX formulations based on other binders. Bouma\textsuperscript{45} studied influence of RDX morphology on sensitivity of RDX based PBXs and found that spherodizing RDX crystals results in minimisation of effect of particle shape on sensitivity of composition. Bouma\textsuperscript{45} also observed that particle size of RDX does not influence cook-off behaviour.

Thermoplastic elastomers (TPEs) are emerging as advanced binders for pressed PBXs\textsuperscript{46}. TPEs also have potential application in low vulnerable ammunition (LOVA) propellants\textsuperscript{47}. TPEs are physically cross linked polymeric systems having superior strain capability in low temperature region like elastomers as well as can be processed at elevated temperature like thermoplastics. This class of polymers offers desired cohesive strength up to moderately high temperature\textsuperscript{48}. TPEs based compositions are also amenable to demilitarization of military system\textsuperscript{49-51}.

Basically, TPEs are copolymers of ABA or AB type where A and B are hard and soft segments respectively. Hard segments ‘A’ result from crystallization/ association of A class monomer components up to moderately high temperatures, Soft segment ‘B’ has amorphous structure arising from B class of monomer components leading to elastic nature\textsuperscript{52} of TPEs up to sub zero temperature. Industrially produced thermoplastic elastomers can be broadly classified into four categories and these polymers discussed in following text.
(i) **Styrene diene block co-polymers:** TPEs of this class comprise of styrene and butadiene/isoprene combinations. Kratons$^{53}$ belonging to this class include styrene – butadiene–styrene (S-B-S), styrene–isoprene–styrene (S-I-S) and styrene – ethylene / butylenes-styrene (S-E/B-S) block copolymers. The co-polymers offer $T_\text{g}$ ranging from -34°C (S-I-S) to -14°C (S-B-S). The polystyrene end blocks trend to cluster together to from sub-microscopic particle which are uniformly distributed throughout mass, producing effect of cross-link network.

(ii) **Polyurethanes:** Polyurethane$^{54}$ class of TPEs contain soft flexible segments of aliphatic polyether or polyester and hard segments of the hydroxyl terminating aromatic polyurethane cross linked by aromatic diisocyanate with low molecular weight chain extender. Hard segment are strongly bonded and tend to segregate in semi crystalline form. Estane is widely known polymer of this class$^{55}$.

![Estane-5731](image)

(iii) **Polyester-ethers:** This class of TPE contain hard (Crystalline) segment formed by aromatic polyester (like polybutylene tere-phthalate) and soft (amorphous) segments resulting from flexible polyether chain (like poly ether glycol). HyTemp produced by Du-Pont has found application in some of the reported sheet explosive compositions$^{31}$.

(iv) **Polyolefin:** Polyolefin class of TPEs are mechano-chemical systems obtained by blending a crystalline polyolefin homopolymer (poly propylene) with ethylene –propylene elastomers. Polyolefin TPEs encompass a broad family of materials with flexible to hard characteristics by tailoring polymer structure. TPEs of this class retain
elastic property over wide range of temperature in the region of -60° to 100°C. Copolymers of ethylene and vinyl acetate (Ethylene vinyl acetate (EVA) copolymers) produced by solution copolymerization at medium pressures belong to this class\textsuperscript{56}. Pendent acetoxy groups of acetate unit in polymer prevent crystallization of the ethylene units thereby transforming crystalline thermoplastic polyethylene into an amorphous rubbery copolymer. It also offers advantage of resistance to oxidation due to saturated structure.

![Ethylene Vinyl Acetate](image)

Fluorocarbon polymers having saturated chemical structure can offer high thermal resistance to explosive composition due to presence of a large proportion of C-F bonds which are stronger than the C-C and C-H bonds. Polymers of this class are also highly fire resistant to oxidation/ozonolysis and chemicals. Homopolymers of the fluorinated monomers are crystalline, and are used as plastics (polytetrafluoroethylene / polytrifluoroethylene). Introduction of amorphous structure needs co-polymerisation to achieve low glass transition temperature. The most widely used copolymers are based on vinylidene fluoride in combination with other fluorinated monomers. Copolymers of vinylidene fluoride and hexa fluoro propylene like viton\textsuperscript{57} are preferred choice for application in HEMs\textsuperscript{58}.
1.9 Objective of the Present Study:

Advancements in technology of warheads are progressing at fast pace. R&D in the area of shaped charge design has led to emergence of systems capable to achieve higher lethality in terms of penetration to armour posing threats to modern tanks. This requires innovative approaches in designing ERA system with capability to counter threat of advanced shape charge devices. There is also a need to introduce additional capability in modern ERA systems to defeat KE projectiles. Present research programme is undertaken to generate data base on new class of sheet explosives by incorporating polymers and explosives with different chemical structures to counter emerging threats. The work will enable to designing of wide range of sheet explosives for advanced systems.

As RDX and crepe rubber are widely reported as component of sheet explosive compositions for military applications, a systematic data was obtained on 80 – 90% RDX-CR compositions as reference. TPEs (Estane & EVA) with combination of hard and soft block were investigated as binder to assess their effect on characteristics of sheet explosive compositions, particularly with respect to mechanical properties. Cast cured HTPB binder system and pre-cured polyurethane (PU) polymer with aromatic units in chain were also evaluated to realize composition with wide range of characteristics. Effect of incorporation of fluoro polymer (viton) and glycidyl azide polymer as additive to PU binder was determined, particularly with respect to energetics of the composition. Powerful explosive, namely HMX and CL-20 were evaluated as HEM component of HTPB based composition to assess their potential as replacement of RDX in sheet explosive composition.

Process parameters were established to obtain wide range of compositions in sheet form. The compositions were subjected to impact, friction and shock sensitivity tests to assess their response to various stimuli. Mechanical properties of samples were determined in terms of tensile strength and percentage elongation. Compositions
were subjected to vacuum stability test to assess their behaviour during storage. Power potential of compositions was determined by subjecting them to standard tests for obtaining VOD. Thermal decomposition pattern was studied by applying DTA/TGA/DSC technique to understand thermal behaviour. Selected compositions were also subjected to detonability studies by initiating them with shaped charges of different calibre.

Comprehensive data generated during this work will be of great significance in designing advanced ERA.

1.10 Scheme of Present Study:

The present thesis is divided into five chapters

**Chapter 1 Introduction:** This chapter gives a brief account of potential of sheet explosives in civil and defence sectors. It includes an overview of sheet explosive compositions developed all over the globe. Evolution of concept of ERA using sheet explosive as key component is also discussed. Studies carried out in this area are summarized. A section is devoted to new class of explosives and polymers having potential of application in advanced sheet explosive compositions. This chapter also brings out objective of present study in the end.

**Chapter 2: Experimental:** This chapter describes broad specification of materials used in preparing sheet explosive compositions. Processing methods adopted for formulations in sheet form is given in brief. Sheet explosive compositions obtained during research work are tabulated. Instrumental and technique methods used during this study for determination of sensitivity with respect to impact/friction/shock sensitivity, thermal stability, mechanical properties and velocity of detonation (VOD) alongwith thermal analysis methods used to understand decomposition pattern are described in this section. Experimental set-up used to determine detonability of formulations of against shaped charge of different calibre is also elaborated.
Chapter 3: Results and Discussion: This chapter presents data generated on RDX/HMX/CL-20/NTO/TATB compositions based on crepe rubber/TPEs/pre-cured polyurethane/HTPB/fluoropolymers during this research work. The chapter is divided into eight sub-chapters for each of the presentation of comprehensive data generated during this research program.

3.1 RDX – Crepe rubber compositions
3.2 RDX – EVA/ESTANE Compositions
3.3 RDX – PU – Viton compositions
3.4 RDX/HTPB based compositions
3.5 HMX/CL-20/HTPB Compositions
3.6 RDX/TATB/HTPB sheet explosive compositions
3.7 RDX/NTO/Estane sheet explosive compositions
3.8 Thermal Studies on Sheet Explosive Compositions

Chapter 4: General Discussion: This chapter discusses major trends obtained for crepe rubber/TPEs/pre-cured polyurethane/HTPB/fluoropolymers based sheet explosive compositions containing RDX/HMX/NTO/TATB as explosive component. The results are analysed and discussed on the basis inherent characteristics of explosives/polymers compositions. An attempt is made to explain data in the light of findings cited in literature.

Chapter 5: Summary
This chapter summarises objective of the present research, experimentations and findings of the present study.
References


(9) Holzman. A.H., “Explosion Clads”, Proceeding of the NATO Advanced Study Institute on the High Energy Working of Metals, Central Institute for Industrial Research, Oslo,


Held M. “Stopping power of explosive reactive armours against different shaped charge diameter or at different angles” Propellants, Explosives, Pyrotechnics, 26, 97-104, 2001.


Norway, 1964.


(17) Held M. “Stopping power of explosive reactive armours against different shaped charge diameter or at different angles” Propellants, Explosives, Pyrotechnics, 26, 97-104, 2001.


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(32) EURENCO GROUPE SNPE, Explosive Charges & Additives Business Unit, 12 quai Henri IV – 75004 Paris – France

(33) Indian Patent No. 153102 A 2 “Process of preparation low velocity of detonation (VOD) sensitive sheet explosive to be used for cladding of metal plate” June 1984


Exceeds that of HMX and its sensitivity is Moderate” Propellants, Explosives, Pyrotechnics 22, 249-255, 1997.


(44) Radwan, M., “Sensitivity and performance of energetic materials based on different types of energetic binder”, ICT 37th 56 / 1-56 / 12, 2006


