Combustion, Explosion, and Shock Waves, Vol. 44, No. 4, pp. 461–477, 2008

Cast Aluminized Explosives (Review)

**P. P. Vadhe,[1] R. B. Pawar,[1]
R. K. Sinha,[1] S. N. Asthana,[1]
and A. Subhananda Rao[1]**

UDC 536.46

Translated from *Fizika Goreniya i Vzryva*, Vol. 44, No. 4, pp. 98–115, July–August, 2008.
Original article submitted October 3, 2007; revision submitted January 25, 2008.

This paper reviews the current status and future trends of aluminized explosives. The major focus is on cast compositions, which encompass both the melt-cast trinitrotoluene (TNT) based and the slurry cast polymer-based compositions. Widely reported RDX and HMX based aluminized compositions with TNT used as a binder are discussed in detail. Various researchers have suggested a 15–20% Al content as an optimum from the viewpoint of velocity of detonation. A higher Al content, however, is incorporated in most of the compositions for a sustained blast effect, due to the potential of secondary reactions of Al with detonation products. The effect of the aluminum particle size on performance parameters (velocity of detonation, etc.) is included. There are some recent works on nanometric Al based compositions, and the results obtained by various researchers suggest mixed trends for RDX–TNT compositions. Studies on nitrotriazol and TNT based compositions bring out their low vulnerability. Some of the interesting findings on ammonium dinitramide and bis(2,2,2-trinitro-ethyl)nitramine (BTNEN) based compositions are also included. The review brings out superiority of polymer based aluminized explosives, as compared to conventional TNT based compositions, particularly, with respect to low vulnerability. In general, aluminized plastic bonded explosives find numerous underwater applications. Ammonium perchlorate (AP) is also incorporated, particularly, for enhancing underwater shock wave and bubble energy. Hydroxyl terminated polybutadiene appears to be the binder of choice. However, nitrocellulose, polyethylene glycol, and polycaprolactone polymer based compositions with energetic plasticizers, like bis-dinitropropyl acetal/formal (BDNPA/F, 1/1 mix), trimethylol ethane trinitrate, and triethylene glycol dinitrate are also investigated. Polyethylene glycol and polycaprolactone polymer based compositions are found to be low vulnerable, particularly, in terms of shock sensitivity. Highly insensitive polymer bonded nitrotriazol based compositions are being pursued all over the globe. The highly insensitive CL-20/AP combination meets the demands of high density and high velocity of detonation. Glycidyl azide polymer and poly nitratomethyl methyl oxetane appear to be binders of interest for plastic bonded explosives in view of their superior energetics. The vulnerability aspects of these compositions, however, need to be studied in detail. Brief information on plastic bonded and gelled thermobaric explosives is also included.

Key words: PBX, HTPB, CL-20, FOX-7, RDX, HMX, NTO, trinitrotoluene, cyclotetramethylene tetranitramine, cyclotrimethylene trinitramine, aluminum, particle size, velocity of detonation, insensitive munitions, munitions with attenuated risk.

---

[1] High Energy Materials Research Laboratory,
Pune 411021, India; hemsociety@rediffmail.com.

Notations

ADN	ammonium dinitramide
AN	ammonium nitrate
AP	ammonium perchlorate
BTNEN	bis(2,2,2-trinitroethyl) nitramine
BDNPA/F	1/1 bis-dinitropropyl acetal/formal
CB	carbon black
CL-20	hexanitrohexaazaisowurtzitane
D2 Wax	desensitized wax (84/14/2 indramic wax 170C/nitrocellulose/lecithin)
DES N-100 or Desmodur N-100	polyisocyanate; aliphatic polyisocyanate
DOA	dioctyl adipate
EIDS	extremely insensitive detonating substances
FOX-7	1,1-diamino-2,2-dinitroethylene
GAP	glycidyl azide polymer
IPDI	isophorone diisocyanate
IPN	isopropyl nitrate
HBX	high blast explosive
HMX	cyclotetramethylene tetranitramine
I-800 Ganex	98.5/1.5 Indramic wax 800/Ganex surfactant
K-10	65/35 dinitroethylbenzene/2,4,6-trinitroethylbenzene
Laminac-styrene	trademark of a polyether binder used in pyrotechnics
MNAMMO	3-methylnitramino-methyl-3-methyloxetane
NC	nitrocellulose
NG	nitroglycerine
NM	nitromethane
NMMO	3-nitratomethyl-3-methyl oxetane
NTO	3-nitro-1,2,4-triazol-5-one
PBX	plastic bonded explosives
PCP	poly(caprolactone)
PDNPA	2,2-dinitropropylacrylate polymer
PEG	polyethylene glycol
PETN	pentaerythritol tetranitrate
PGN	polyglycidyl nitrate
PolyNIMMO	polynitromethylmethyloxetane
PVN	polyvinyl nitrate
PU	polyurethane
RDX	cyclotrimethylene trinitramine
TEGDN	triethylene glycol dinitrate
TMETN	trimethylolethane trinitrate
TNT	trinitrotoluene
Viton	vinylidene fluoride-perfluoropropylene copolymer

INTRODUCTION

Advent of RDX and HMX led to giant strides in the area of high blast explosives. RDX and HMX used in conventional TNT based cast compositions contribute toward improvement in velocity of detonation of the explosive composition due to superior heat of formation, oxygen balance, and density. It leads to improved fragment velocity and jet energy of warheads. The improvement in impulse leading to greater cratering and fragmentation effects requires addition of metal powder (Al, B, and Zr), generally aluminum [1–3]. Anderson [4] has reviewed the use of Al powder in plastic bonded explosives and established its potential as a total energy enhancer.

The first use of Al to increase the blast performance of explosives was patented by Roth in 1900 [1]. Exhaustive studies have been carried out to evaluate the effect of the Al content on the characteristics of explosive compositions [5]. Al powder is available in a number of grades and particle sizes ranging from a "bomb" grade flake (MIL-A-512) to spherical particles (<10 μm) (MIL-A-23950). Nanometric aluminum has also evinced interest during recent times.

Owing to the involvement of Al in secondary reactions in the Taylor rarefaction region behind the detonation wave, the classical thermochemical codes based on the Jones–Wilkins–Lee (JWL) and Becker–Kistiakowsky–Wilson (BKW) equations of state of explosion products do not provide accurate descriptions of the detonation phenomenon. Consequently, prediction of performance of these nonideal explosives is a difficult task. Over the last three decades, there has been a continued effort to understand the chemical, thermodynamic, and hydrodynamic interaction between decomposition products of composite explosives. However, it is widely accepted that the reaction of Al is relatively slow in the Chapman–Jouguet plane due to coating of Al particle by Al_2O_3 having a high melting point (2030°C), which impedes its reactivity. Thereby, a large amount of energy is liberated during subsequent reactions of Al with primary detonation products of high explosives, leading to sustained high pressure for longer duration [6]. The overall outcome of Al incorporation in high explosives is the enhancement of late-time effects, such as higher temperature, incendiary effect, air blast, and enhanced damage due to bubble energy during underwater blast [7].

Exhaustive studies have brought out that the velocity of detonation of cast charges continuously decreases on addition of Al beyond 20% [8–10]. It has been established that the heat of explosion Q_v increases with increasing Al content C_{Al} [11], whereas the volume of gaseous products V_0 decreases (Table 1). Consequently, the maximum power Q_vV_0 is reached at the 18% Al content, and the optimum content of Al is considered to be 20%. Nevertheless, explosive compositions with a higher Al content are of interest for blast producing compositions. Brisance of aluminized compositions increases with the Al content up to 70% Al [9]. They are also of interest for underwater applications.

TABLE 1

Effect of Aluminum Content on Heat of Explosion and Volume of Gaseous Products for TNT/Al Compositions

C_{Al}, %	Q_v, kJ/kg	V_0, liter/g	Q_vV_0, 10^4 kJ · liter/kg^2
0	4226	0.750	318
9	5188	0.693	360
18	6485	0.586	381
25	7280	0.474	343
32	7657	0.375	289
40	8452	0.261	222

The basic chemical processes involving Al in the explosion phenomenon resulting in the blast effect are summarized below:

$$2\text{Al}_{(\text{s})} + 3\text{H}_2\text{O}_{(\text{g})} \to \text{Al}_2\text{O}_{3\,(\text{s})} + 3\text{H}_{2\,(\text{g})} + 866 \text{ kJ/mole},$$

$$2\text{Al}_{(\text{s})} + 3\text{CO}_{2(\text{g})} \to \text{Al}_2\text{O}_{3\,(\text{s})} + 3\text{CO}_{(\text{g})} + 741 \text{ kJ/mole},$$

$$2\text{Al}_{(\text{s})} + 3\text{CO}_{(\text{g})} \to \text{Al}_2\text{O}_{3\,(\text{s})} + 3\text{C}_{(\text{s})} + 1\,251 \text{ kJ/mole}$$

(the subscripts "s" and "g" refer to the solid and gas phases, respectively).

The pressure–time profile of the aluminized composition exhibits a relatively lower pressure, but the pressure is sustained for a longer duration (by a factor of 2 or 3), as compared to that in the case of corresponding non-aluminized explosives, due to an exothermic reaction of Al with detonation products behind the reaction zone in the detonation wave front [12]. It is well known that Al reacts not only with oxygen fractions of detonation products but also with the nitrogen fraction to form aluminum nitride AlN:

$$2\text{Al}_{(\text{s})} + \text{N}_{2(\text{g})} \to 2\text{AlN}_{(\text{s})} + 346 \text{ kJ/mole}.$$

The above-given reaction schemes suggest that Al oxidation may occur with reduction of H_2O to H_2 and with reduction of CO_2 to either CO or solid carbon C. Application of the BKW code does not indicate formation of solid carbon. However, Volk et al. [13] have experimentally established significant involvement of Al toward reduction of CO_2 to solid carbon. Based on the analysis of detonation products [13], Baudin and

TABLE 2

Characteristics of Tritonal vis-à-vis TNT

Physical properties	TNT	80/20 TNT/Al
Molecular weight	227	—
Oxygen balance, %	−73.9	−72
Heat of formation, cal/g	−44.2	−44.2
Enthalpy of formation, cal/g	−62.5	—
Heat of explosion, cal/g	1210	1770
Density, g/cm^3	1.654	1.71–1.78 (theoretical 1.793)
Decomposition temperature, °C	240	—
Velocity of detonation, km/sec	6.9	6.52 for $\rho = 1.77$ g/cm^3
Sensitivity to impact, cm (weight 2 kg)	90	84
Peak pressure, GPa	17.8	11.0

TABLE 3

Effect of Aluminum Particle Size on the TNT/Al System

C_{Al}, %	a, μm	ρ, g/cm^3	D, km/sec	Q_d, kJ/kg
10	12	1.67	5.72	5307
	Alex		6.51	5479
30	21	1.82	5.74	6184
	12		6.23	6519
	2		6.48	6660
	Alex		6.63	6749

Bergues [14] concluded that only 18% of the molar fraction of H_2O and up to 50% of the molar fraction of CO_2 were reduced by Al. The energy contribution Q_{Al} of this reaction pattern is 20.126 MJ/kg of Al. An empirical reactive flow model coupled with reaction kinetics for detonation and combustion was developed by Miller et al. [15] on the basis of experimental finding and thermochemical calculations. Baudin and Bergues [14] studied the reaction behavior of Al, HMX, and AP based high explosives. They developed a model for predicting high explosive performance in aerial small-scale tests and underwater explosions.

Although aluminized RDX and HMX based compositions with TNT as a binder find wide application in today's scenario, efforts are on to develop insensitive munitions (IM) widely known as munitions with attenuated risk (MURAT) to ensure that it does not detonate under any conditions other than its intended mission to incapacitate a target. Insensitive munitions utilize a polymeric binder in place of TNT in the compositions. It is desired that the munitions be immune to the impact of high-velocity fragments or a bullet and burn rather than detonate at extreme temperatures generated due to fire. The safety during packing, handling, transportation, and storage of insensitive munitions is high relative to that of conventional munitions.

1. CONVENTIONAL TNT BASED EXPLOSIVE COMPOSITIONS

1.1. TNT/Al Compositions

The well-reported aluminized explosive composition Tritonal contains 80% TNT and 20% flaked Al [16]. It was developed and standardized in the USA during WWII for realizing an improved blast effect. The blast properties of Tritonal (80/20) are widely reported in the literature [17–19] (see Table 2).

Tritonal is a general-purpose composition with moderately good performance for fragmentation and air-blast applications, particularly, in navy and air force bombs [4]. The desensitized tritonal is referred as destex.

Tao et al. [20] studied the effect of the particle size a on the heat release rate using Fabry–Perot laser interferometery. Brosseau [21] reported that addition of nanometric Al (Alex) to the TNT/Al system leads to a remarkable increase in velocity of detonation D as well as heat of detonation Q_d (Table 3).

1.2. Aluminized RDX/TNT Based Compositions

This class of explosive compositions is finding wide application in current scenario in view of much superior performance than tritonal. Although incorporation of Al in Composition B results in lowering of velocity of detonation, it leads to an increase in heat of detonation (Table 4) [22–23]. However, Gurney constants[2] (G_C) for aluminized and non-aluminized explosive compositions lead to contradictory results. Thus, Torpex (18% Al) shows G_C = 2710 m/sec close to cyclotol (70/30 RDX/TNT) and higher than those for RDX and composition B (G_C = 2680 m/sec). On the other hand, H-6, HBX-1, HBX-3, and tritonal exhibit smaller G_C

---

[2] Energetic coefficient calculated per unit mass of the explosive charge, which characterizes the velocity of motion of body fragments.

TABLE 4

Characteristics of Aluminized RDX/HMX/TNT Systems

Explosive	ρ, g/cm^3	D, km/sec	p, GPa	ΔH_f, kJ/mole	G_C, m/sec
Composition B: 59/40/1 RDX/TNT/Wax	1.68	7.50	29.3	3.35	2680
Cyclotol: 70/30 RDX/TNT	1.71	8.06	32.0	−11.60	2710
Dentex: 48.5/33.5/18/0.5 RDX/TNT/Al/Wax and paraffin added above 100%	1.75	7.78	—	—	—
Torpex: 42/40/18 RDX/TNT/Al	1.81	7.60	23.2	0.59	2710
H-6: 45.1/29.2/21.0/4.7 RDX/TNT/Al/D2 Wax	1.76	7.49	24.5	−4.56 [24]	2620
HBX-1: 40.4/37.8/17.1/4.7 RDX/TNT/Al/D2 Wax	1.712	7.31	22.0	−8.25 [22, 23]	2470
HBX-3: 31.3/29.0/34.8/4.9 RDX/TNT/Al/D2 Wax	1.85	7.53 [24]	20.6	−8.71 [25]	2230
Tritonal: 80/20 TNT/Al	1.72	6.52	20.9	−22.11	2320
Destex: 74.7/18.7/4.7/1.9 TNT/Al/D2 Wax/CB	1.69	6.74	17.9	−29.64 [26]	—

Note. p is the maximal pressure in the detonation wave.

TABLE 5

Effect of the Al Particle Size on Velocity of Detonation and Heat of Detonation of Composition B

Mixture type	Al, %	a, μm	ρ, g/cm^3	D, km/sec	Q_d, kJ/kg
Composition B	0	—	1.69	7.89	5389
Composition B/Al	10	21	1.74	7.74	5621
Composition B/Al	10	12	1.74	7.74	5816
Composition B/Al	10	2	1.74	7.68	6004
Composition B/Al	10	Alex	1.74	7.60	5927

values, as compared to non-aluminized Composition B.

Dentex, Torpex, H-6, HBX-1, and HBX-3 are examples of well-known 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.

It is reported that incorporation of nanometric Al in Composition B instead of micro-sized Al leads to reduction in velocity of detonation, in contrast to the case with TNT where the velocity of detonation increases. Reduction in the Al particle size is found to increase heat of detonation of Composition B (Table 5) as in the case of tritonal [27–29].

1.3. Aluminized HMX Based Compositions

According to the general trend, addition of Al to the HMX/TNT based composition also leads to reduction in velocity of detonation (Table 6). The Al incorporated octol, designated as HTA-3 [30], finds application for its blast capability combined with brisance.

Gogulya et al. [31] determined the effect of variation in the Al content and particle size on the temperature and pressure profiles of the HMX/Al compositions (Table 7). They monitored the interaction of Al with HMX detonation products using a dual-channel pyrometer interfaced with a LiF window.

The results of the study [31] indicate that velocity of detonation of the HMX/Al combination is of higher magnitude in the case of compositions containing Al particles with $a = 150$ μm. The peak pressures for compositions containing Al particles with $a = 150$, 20, and 0.5 μm, however, are commensurable. Gogulya et al. [31] also found that incorporation of 5% Al in HMX led to slightly higher or nearly the same temperature of detonation products in the first microsecond as for pure HMX (3772°C) irrespective of the Al particle size. An increase in the Al content, however, led to a decrease in temperature of detonation products below the level typical for pure HMX, except in the case of a mixture with 25% Al of 150 μm size. They interpreted that the energy needed for Al heating is compensated by the heat released during oxidation up to 5% Al. It was inferred that the relative sizes of Al and HMX particles played a major role. HMX particles of size less than that of Al ($a = 150$ μm) surround the latter and are available for the detonation reaction, whereas $a = 0.5$ μm Al particles being of smaller size than HMX, the latter are

TABLE 6

Aluminized HMX/TNT Based Compositions

Explosive	ρ, g/cm^3	D, km/sec	p, GPa	ΔH_f, kcal/mole	G_C, m/sec
Octol: 70/30 HMX/TNT	1.72	8.40	—	—	—
HTA-3: 49/29/22 HMX/TNT/Al	1.946	7.87	—	1.05 [30]	—
H-6: 45.1/29.2/21.0/4.7 RDX/TNT/Al/D2 Wax	1.76	7.49	24.5	−1.09 [24]	2620

TABLE 7

HMX/Al Characteristics
Depending on the Al Particle Size and Content [31]

a, μm	$C_{\rm Al}$, %	ρ, g/cm^3	$\rho/\rho_{\rm max}$, %	D, km/sec	$p_{\rm max}$, GPa
Pure HMX	—	1.81	—	8.76	43.2
150	5	1.84	95	8.74	38.8
	15	1.89	95	8.66	36.3
	25	1.95	95	8.55	32.1
50	5	1.84	95	8.73	33.5 ± 0.2
	15	1.88	94	8.63	
	25	1.93	94	8.44	
20	5	1.83	95	8.72	40.0
	15	1.87	94	8.55	35.0
	25	1.92	93	8.37	35.0
0.5	5	1.84	95	8.66	40.2
	15	1.87	94	8.35	34.5
	25	1.91	93	7.97	24.5

enveloped in a layer of Al particles in this case, leading to inhibition of HMX decomposition in the detonation wave front. This is reflected in the pressure drop being slower in the case of compositions with 150 μm Al.

1.4. Aluminized PETN Based Compositions

The explosive parameters determined for PETN/Al systems (Table 8) also reveal that velocity of detonation reaches the highest value for the composition with the lowest Al content.

Tao et al. [20] studied aluminized PETN using Fabry–Perot laser interferometery. They analyzed thermodynamics and hydrodynamics of detonation by applying the reactive flow model for the nature of the reaction zone and subsequent expansion of reaction products (Taylor wave). It was inferred that high detonation temperatures of PETN increased the mass transport rate and, hence, shorten the Al reaction time scale.

TABLE 8

Explosive Parameters for PETN/Al Systems [20]

PETN/Al, %	ρ, g/cm^3	D, km/sec	$\rho_{\rm CJ}$, GPa
100/0 [32]	1.67	7.98	31.0
95/5	1.78	8.10	32.0
90/10	1.80	8.00	32.5
80/20	1.89	7.80	32.0

2. LOW VULNERABLE NTO/TNT BASED COMPOSITIONS

It is well known that NTO belongs to the category of insensitive explosives being much less vulnerable to hazard stimuli than RDX/HMX. Extensive work on melt-cast compositions containing NTO/TNT/Al has been undertaken at U.S. Air Force (USAF) [19] to realize low vulnerability despite of using TNT as a binder. These compositions are designated as TNTO (Table 9).

To overcome the exudation problem observed due to low melting D2 Wax in TNTO IV, which is also known as the AFX-644 (air force explosive) composition, D2 Wax was substituted with a combination of Indramic-800 and Ganex WP-660 (98.5/1.5) in the composition AFX-645. The velocity of detonation of AFX-644 and AFX-645 were almost similar to that of the Tritonal standard. Their friction and impact sensitivities are beyond the upper limit of the instrument, suggesting 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 classification for both storage and transportation.

3. ADN AND BTNEN AS COMPONENTS OF ALUMINIZED EXPLOSIVE COMPOSITIONS

3.1. ADN Based Composition

Miller et al. [15] studied pressed aluminized ADN compositions. Their velocity of detonation, however, is on lower side, and even addition of nanometric Al did

TABLE 9

Sensitivity and Performance of Melt-Cast Aluminized TNT/NTO

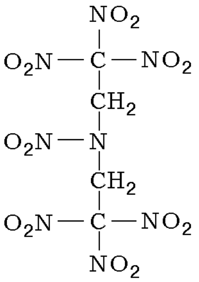
Composition NTO/TNT/Al/binder	ρ, g/cm^3	D, km/sec	d_{cr}, mm	$H_{50\%}$, cm	H	H_e, J
TNTO 0 38/40/16/6 (D2 Wax)	—	—	—	>200.5	41.2	0.040
TNTO I 42/34/19/5 (D2 Wax)	1.76	6.67	25–51	>200.5	—	—
TNTO II 42/32/19/7 (D2 Wax)	1.74	6.84	32–35	>200.5	53.0	0.040
TNTO III 42/30/19/9 (D2 Wax)	—	—	—	>200.5	—	—
TNTO IV 40/30/20/10 (D2 Wax)	1.70	6.96	41–43	>200.5	60.8	0.040
AFX-645 48/32/12/8 (I-800 Ganex) [18]	1.63	6.83	51–64	>200.5	60.8	0.040

Notes. $H_{50\%}$ is the sensitivity to impact (load of 5 kg), H is the sensitivity to friction determined by the BAM method (BAM is an abbreviation for the Federal Institute for Materials Research and Testing, Germany), H_e is the sensitivity to the electrostatic discharge, and d_{cr} is the critical diameter.

not influence velocity of detonation of ADN in its physical mixtures. Viton was found to have a positive effect on increasing velocity of detonation (Table 10, where $\rho_{\max}$ is the maximum theoretical density; $\bar{\rho}$ and $\bar{D}$ are the average values of density and velocity of detonation).

3.2. BTNEN Based Compositions

BTNEN:



Molecular formula: $C_4H_4O_{14}N_8$
Molecular weight: 388.21
Density: 1.96 g/cm^3
Heat of formation: nearly zero
Oxygen balance: +16.5%
Velocity of detonation: 8.5–8.66 km/sec
Particle size: needle-shaped crystals 15–40 μm in diameter and up to 500 μm long

Gogulya et al. [31] investigated the effect of Al and its particle size in a BTNEN based composition. They prepared 85/15 BTNEN/Al combinations by mixing the components in a metal vessel in an inert liquid (hexane) in the presence of porcelain balls. A uniform distribution of Al particles in bulk was established by microscopic studies. BTNEN needles were transformed to elongated particles during the process, with the transverse size approximately equal to the diameter of original needles. The explosive charges 20 and 40 mm in diameter were pressed by applying cold unidirectional pressing to achieve density of about 93% of the theoretical value. These researchers observed that addition of Al results in a decrease in velocity of detonation and peak pressure $p_{\max}$ (Table 11). They observed that BTNEN renders the composition more sensitive than even typical secondary explosives including PETN. It may be an outcome of a positive oxygen balance of BTNEN in contrast to a negative oxygen balance of RDX and HMX. BTNEN mixtures with 0.1 μm Al particles are even more sensitive (Table 12). This is attributed to chemical interaction of BTNEN decomposition products with Al in hot spots [32].

4. PLASTIC BONDED EXPLOSIVES

TNT based compositions are not able to retain the structural integrity on heating by frictional forces in high-speed supersonic missile systems eventually leading to “hot spot” formation. It renders the system prone to fast cook-off temperature and may result in premature functioning/explosion in the trajectory. Storage at high temperatures, particularly, in tropical countries also limits the storage life of TNT based ammunitions. Plastic bonded explosives (PBX) based on a polymeric binder offer a superior solution. Moreover, aluminized PBX compositions have low end-off viscosity, as compared to TNT based aluminized compositions, rendering filling and casting into warheads an easy task. The Al particle size in the range of $a = 120$–250 μm is akin to achieve low viscosity.

TABLE 10

Explosive Properties of Pressable ADN/Al Based Compositions with a Change in Al Particle Size [15]

Composition	$\bar{\rho}$, g/cm^3	$\bar{D}$, km/sec	$\rho/\rho_{\max}$, %
ADN	1.69 1.604	4.24 4.19	92.2 87.2
72/25 ADN/Al (3 μm Al)	1.794	4.10	90.5
73/23/3 ADN/Al/Viton (50 μm Al)	1.714	5.03	86.3
97/3 ADN/Viton	1.752 1.735	4.25 4.06	95.0 94.0

TABLE 11

Properties of the 85/15 BTNEN/Al Composition [31]

a, μm (charge diameter)	ρ, g/cm^3	$\rho/\rho_{\max}$, %	D, km/sec	$p_{\max}$, GPa (ρ, g/cm^3)	Q_v, kJ/kg (ρ, g/cm^3)
0	1.870	95.4	8.50	36.4 (1.88)	5230 (1.89)
0	1.909	97.4	8.66	—	—
150 (20)	1.965	96.1	8.38	—	8280 (1.94)
15 (20)	1.955	95.6	8.30	35.6 (1.97)	8280 (1.94)
7 (20)	1.955	95.6	8.28	—	8600 (1.94)
0.1 (20)	1.910	93.4	8.07	34.1 (1.92)	—
0.1 (20)	1.914	93.6	8.04	—	—
0.1 (40)	1.900	93.0	7.92	—	8350 (1.90)
0.1 (40)	1.830	89.5	7.66	—	—

TABLE 12

Critical Pressure of Explosions: Comparison of Mechanical Sensitivity

Explosive	p_{cr}, GPa
Mercury fulminate/lead azide	$0.20 \pm 0.01/0.38 \pm 0.03$
PETN	0.93 ± 0.03
BTNEN	0.79 ± 0.03
TNT/RDX/HMX	$1.35 \pm 0.03/1.15 \pm 0.03/1.00 \pm 0.03$
BTNEN/Al (0.1 μm)/(7.0 μm)	$0.55 \pm 0.02/0.74 \pm 0.02$
HMX/Al (0.1 μm)/(7.0 μm)	$0.67 \pm 0.03/0.95 \pm 0.03$

4.1. RDX/HMX Based PBX Compositions

Development of aluminized PBX compositions for underwater applications commenced in the late 1950s. Both pressed and castable PBX compositions were introduced during the 1960s [33]. Castable non-aluminized PBX compositions based on Laminac-styrene binders were developed at the initial stage. PBXN-101 (82/18 HMX/Laminac-styrene), PBXN-102 (59/23/18 HMX/Al/Laminac-styrene), and PBXN-104 (70/30 HMX/Laminac-styrene) belong to this class. They became obsolete, however, due to drawbacks of being physically hard and highly sensitive, as was revealed by large-scale sensitivity tests. PEG and HTPB evinced interest as binders in PBX compositions instead of Laminac-styrene [4]. However, HTPB became a preferred choice as a binder. Aluminized PBX compositions based on RDX with HTPB as a binder are widely

TABLE 13

Composition and Characteristics of Aluminized RDX Based Castable PBX Compositions

Explosive	RDX/Al/HTPB composition	ρ, g/cm^3	D, km/sec
HXA-177 [35]	67/15/18	1.60	7.58
KS-22a [36–38]	67/18/15	1.64	7.40
PBXN-109 [34, 4]	64/20/16	1.65	7.20
HXA-171 [35]	52/30/18	1.67	7.20
HXA-172 [35]	42/40/18	1.72	7.05
HXA-173 [35]	32/50/18	1.77	6.55

TABLE 14

Composition and Explosive Properties of Aluminized PBX Compositions [39]

RDX/Al/HTPB composition	$\rho_{\max}$, g/cm^3	ρ, g/cm^3	D, km/sec	$p_{d,\text{calc}}$, GPa
85/0/15	1.586	1.578	7.66	23.8
80/5/15	1.609	1.594	7.53	22.9
75/10/15	1.630	1.610	7.50	22.3
70/15/15	1.670	1.630	7.58	22.4
65/20/15	1.680	1.646	7.26	22.0
60/25/15	1.709	1.680	7.11	21.8

reported in the literature (Table 13). These compositions are reported to be inducted as the main charge fills in the anti-ship Penguin missile, Hellfire missile [34], and penetrator bombs, as well as for underwater applications.

The effect of the Al content on the performance of RDX-HTPB based aluminized PBX compositions was also studied at the High Energy Materials Research Laboratory (HEMRL, Pune, India) [39]. The Al content of 15% was found to be the optimum value in terms of velocity of detonation of the aluminized composition (Table 14). The aluminized PBX compositions developed at HEMRL exhibited low impact sensitivity ($H_{50\%} = 115$–129) and high chemical stability: they evolved less than 1 cm^3 of the gas in a vacuum stability test at 120°C for 48 h. The compression strength of the compositions ranged from 1 to 1.2 MPa.

Volk and Schedlbauer [40] observed a decrease in density (1.63 to 1.62 g/cm^3) and velocity of detonation (7580 to 7350 m/sec) of HXA-123 (70/15/15 RDX/Al/HTPB) on introduction of 5 μm Al (Alcan 400) to an extent of 15%. A life assessment study of Rowanex 1400 (66/22/12 RDX/Al/HTPB) has been undertaken at 60°C for 15 months. The samples withdrawn at different intervals were subjected to chemical analysis, differential thermal analysis (DTA), differential scanning calorimetry (DSC), and spectroscopic studies, as well as dynamical mechanical analysis (DMA). The simulation studies predicted a shelf life of 20 years [41, 42].

TABLE 15

Composition and Characteristics of Aluminized HMX Based Castable PBX Compositions

Explosive	HMX/Al/HTPB composition	ρ, g/cm^3	D, km/sec
PBXW-114 [4]	78/10/12	1.72	8.23
PBXI-1[21]	74/10/16	1.67	7.75
PBXI-3 [21]	64/20/16	1.72	7.45
CD-04 [43]	68/20/12	1.73	7.78
KS-33D [38]	80/10/10	1.75	8.00
PBXN-113 [44] PBXIH-135 [45]	45/35/20	1.68	6.98

HMX based aluminized compositions are also well studied. As expected, they offer superior density and velocity of detonation, as compared to aluminized RDX based compositions (Table 15).

Radwan [46] studied the effect of incorporation of Al up to 30% at the cost of octogen (HMX) in polyurethane binder based PBX compositions, to the reference 84/16 HMX/PU composition. His findings (Table 16) revealed a decrease in brisance (B) and specific volume (V_0) of gases produced, as well as in velocity of detonation to an extent of ≈5%, whereas the heat of explosion (Q_v) and the temperature of explosion (T_v) exhibited a marked increase. The force of explosion (F) reached the maximum value at a 15% Al content. The power of the explosive in terms of the characteristic product Q_vV_0, i.e., the heat of explosion and brisance, reached the maximum value at a 25% Al content. The sensitivity to impact ($H_{50\%}$) decreased markedly (20%) with an increase in the Al content. However, the compositions were sensitive to detonator No. 8. A typical aluminized HMX based composition (65/20/15 HMX/Al/HTPB) is assigned a life of 67 years at 25°C [47].

Polycaprolactone (PCP) is also finding application as a binder for cast PBX compositions. The major advantage of PCP over HTPB is its miscibility with the nitrate ester class of plasticizers [48, 49]. The PCP/TMETN combination offers an advantage of low vulnerability without penalty on energetics. Aluminized HMX/PCP based compositions are also reported [17] (see Table 17).

TABLE 16

Measured and Calculated Characteristics of Aluminized HMX Based PBX Compositions [46]

C_{Al}, %	D, km/sec	B, kPa	V_0, cm^3/g	Q_v, kJ/kg	T_v, K	$H_{50\%}$, cm	F, kJ/g	V_0Q_v, 10^4kJ · liter/kg^2
0	7.01	1073	1030	3974	2974	50	1.145	409
5	—	1070	972	4694	3320	53	1.197	456
10	—	1059	902	5500	3715	56	1.244	496
15	6.82	1050	831	6286	4070	60	1.237	522
20	—	972	760	7072	4410	66	1.184	537
25	—	948	689	7858	4730	71	1.027	541
30	5.64	868	631	8031	4870	74	0.964	506

TABLE 17

Performance of PCP Based Aluminized Compositions [17]

Explosive	HMX/Al/TMETN/PCP composition	ρ, g/cm^3	D, km/sec	Q_v^*, %
RX-35-DW	49.5/18/24.84/7.66	1.765	7.33	105
RX-35-EN	43.89/23.13/25.24/7.74	1.787	7.20	117
RX-35-EK	39.49/27.98/24.83/7.70	1.814	7.06	148

Note. Q_v^* is the blast energy, as compared to tritonal (80/20 TNT/Al).

TABLE 18

Composition and Characteristics of AP Incorporated Aluminized PBX Compositions

Explosive	RDX/AP/Al/HTPB composition	ρ, g/cm^3	D, km/sec	d_{cr}, mm
PBXW-115/PBXN-111 [51]	20/43/25/12	1.790	5.97–6.20	37.6
DXD-03 [52]		1.78	5.49–5.70	—
B 2211/PBXW-115(Aust) [51, 53]		1.79–1.81	5.50	65–86
FPX-7 [51]	20/40/25/15	1.80	5.50	50
KS-57 [37, 38, 54]	24/40/24/12	1.84	5.62	64
HXA-174 [35]	27/25/30/18	1.70	5.87	—
CD-06 [43]	35/23/32/10	1.81	6.98	—
HXA-178 [35]	42/25/15/18	1.63	6.63	—
PBXN-103 [55] (PBXW-100)	AP/Al/NC/TMETN-TEGDN (40/27/4/25/2.3)	1.89	6.20–6.31	27.3
PBXN-105 [55]	RDX/AP/Al/PEG/(BDNPA/F) (7/49.8/25.8/3.13/14.47)	1.90	5.90	60.9
PBXW-123 [50]	AP/Al/TMETN/PCP (44.8/30.2/18.8/6.2)	1.92	5.50	>126

4.2. AP Incorporated Aluminized PBX Compositions

AP based PBX compositions (Table 18) with HTPB as a binder are reported in the literature, particularly, for underwater applications to enhance underwater shock wave and bubble energy. PBXW-115 or PBXN-111 offer a superior alternative to conventional aluminized explosive compositions. PBX compositions equivalent to PBXW-115 also appear under different designations (see Table 18). Variations in reported characteristics of these compositions, particularly, with re-

TABLE 19

Influence of Al and AP on the Total Energy and Detonation Energy [4]

Explosive	Composition	Q_Σ, cal/g	Q_d, cal/g
RDX	—	1204	1141
PBXW-108	RDX/HTPB (85/15)	1238	883
PBXW-109	RDX/Al/HTPB (65/20/15)	1885	796
PBXW-115	RDX/AP/Al/HTPB (20/43/25/12)	2025	351

TABLE 20

Performance/Application Equivalency of PBX with Conventional TNT Based Compositions [4]

Explosive type and application	Warhead applications	Equivalent compositions	
		non-PBX	PBX
General purpose	Bomb filling	H-6 Tritonal	PBXN-109 (64/20/16 RDX/Al/binder) PBXC-117 (71/17/12 RDX/Al/binder)
High brisance	Shaped charges, fragmentation	Octol	PBXN-110 (88/12 HMX/binder)
Brisance	Shaped charges, fragmentation	Composition B Cyclotols	PBXN-106 (75/25 RDX/binder) PBXN-107 (86/14 RDX/binder) PBXW-108 (85/15 RDX/binder) AFX-108 (82/18 RDX/binder)
Metal acceleration	Shaped charges	Tetryl CH-6	PBXN-5 (95/05 HMX/binder) PBXN-6 (95/05 RDX/binder) PBXN-7 (60/35/05 RDX/Al/binder)
Underwater shock, and bubble	Torpedoes, mines: anti-devices	H-6 HBX-1	PBXN-103 (40/27/33 AP/Al/binder) PBXN-105 (7.0/49.8/25.8/17.4 RDX/AP/Al/binder) PBXW-115 (20/43/25/12 RDX/AP/Al/binder)

spect to the critical diameter, is probably due to different sources of RDX used in the composition. Nitrocellulose (NC) and PEG binder based compositions are also mentioned in the literature. PEG based compositions offer a higher critical diameter. A typical PCP based composition with a critical diameter >126 mm is reported as PBXW-123. The composition exhibits initiation with a shock wave of 8 GPa, as compared to 5.9 GPa for PBXN-103 [50].

Incorporation of AP as replacement of RDX results in significant improvement in the total energy Q_Σ, whereas the detonation energy Q_d decreases [4] (Table 19).

AP incorporated HMX based PBX compositions have also evinced interest. Baudin and Bergues [56] studied the reaction behavior of Al in the HMX based composition B3103 (51/19/30 HMX/Al/binder) and HMX/AP based high explosive composition B3100 (42/9/19/30 HMX/AP/Al/binder). Composition B3312 (51/19/30 HMX/LiF/binder) was selected as a reference explosive, where Al was replaced by LiF having mechanical impedance characteristics similar to Al and being known to remain inert in a reactive medium. Almost similar velocities of detonation for explosives B3103 (7760 m/sec) and B3212 (7790 m/sec) clearly established that Al acts like LiF and is not oxidized in the Chapman–Jouguet plane. Replacement of HMX with AP resulted in improved ballistic performance, which may be due to additional supply of oxygen made available by AP for the greater extent of the oxidation process.

Aluminized PBX compositions having performance almost equivalent to that of aluminized TNT based explosives are potential candidates for a wide range of systems (Table 20) with the added advantage of low vulnerability.

TABLE 21

French “B series” and American PBXW Compositions

Explosive	NTO	RDX	HMX	AP	Al	Binder
PBXW-121 [58]	63	10	—	—	15	12 (HTPB)
PBXW-122 [59, 60]	47	5	—	20	15	13 (HTPB)
PBXW-124 [60]	27	20	—	20	20	13 (HTPB)
PBXW-125 [60]	22	20	—	20	26	12 (HTPB)
PBXW-126 [60, 61]	22	20	—	20	26	12 (PU)
B 2245 [62]	8	12	—	43	25	12 (HTPB)
B 2233 [63]	31	—	6	28	10	15 (HTPB)
PBXW-125 mod. 2 [17]	10	25	—	20	33	12 (HTPB)

TABLE 22

Composition of GAP
Based Aluminized PBX Compositions
(with and without AP) [7]

Explosive	RDX	Al	GAP	AP
GHX 86	82	—	18	—
GHX 78	67	15	18	—
GHX 83	62	20	18	—
GHX 84	57	25	18	—
GHX 85	52	30	18	—
GHX 87	42	40	18	—
GHX 89	27	50	18	—
GHX 99	47	$30^{(a)}$	23	—
GHX 100	47	$30^{(b)}$	23	—
GHX 101	47	$30^{(c)}$	23	—
GHX 76	42	15	18	25
GHX 80	37	20	18	25
GHX 81	32	25	18	25
GHX 82	27	30	18	25

Notes. (a) Specific surface 0.134 m^2/g and average particle size 150 μm; (b) specific surface 0.229 m^2/g and average particle size 50 μm; (c) specific surface 1.144 m^2/g and average particle size 5 μm.

4.3. NTO Based Aluminized PBX Compositions

An exhaustive review on NTO based explosive compositions containing AP and Al is published by Smith and Cliff [57]. AP incorporated NTO based aluminized PBX compositions were developed at SNPE and designated as “B series” compositions, which are referred as PBXW in the USA (Table 21).

PBXW-126 having a density of 1.80 g/cm^3 and velocity of detonation of 6.47 km/sec with a detonation pressure of 16.0 GPa [64] is reported to be superior among PBXW compositions. The peak pressure generated by PBXW-126 is found to be 1.29 times to that of TNT and 1.22 times to that of PBXN-109 [64]. Its delivered impulse is 1.06 and 1.25 times of that of TNT and PBXN-109, respectively. The unconfined critical diameter of PBXW-126 is smaller than 76 mm, establishing its high order of insensitivity. PBXW-124 and PBXW-122 have critical diameters of 76–109 and 178 mm, respectively, meeting the insensitivity criteria. A variant of PBXW-125 referred as mod. 2 is claimed to be more effective for application in warheads used against hard targets [17].

4.4. GAP and PolyNIMMO Based Aluminized PBX Compositions

Keicher et al. [7] studied aluminized PBX compositions (Table 22) with GAP plasticized with 1/1 BDNPA/F as a binder cured with Desmodur N-100. The better oxygen balance of GAP assists in completion of reactions of Al. Keicher et al. [7] observed nearly the same impulse and peak pressure for the formulations containing Al in the range of 15–33%. A further increase in the Al content resulted in a decrease in the peak pressure. The bubble energy reached the maximum value at a 40% Al content.

Incorporation of AP in the compositions (see, e.g., GHX 76 and GHX 82 in Table 22) results in an increase in the bubble energy, although the peak pressure remains unaffected. Although the bubble energy increases with the Al content, the Al particle size (5–150 μm) did not have any significant effect on it. The pressure and impulse were also not influenced by the Al contents up

TABLE 23

Influence of the AP Particle Size on Performance of GAP Based Aluminized PBX Compositions [65]

Explosive	RDX	GAP	Al $5\ \mu$m	AP		ρ, g/cm^3	D, km/sec	Sensitivity	
				200 μm	5 μm			to impact, N $\cdot$ m	to friction, N
GHX 82	27	18	30	25	—	1.91	6.81	2.0–3.0	20–24
GHX 116	27	18	25	30	—	1.88	6.75	3.0	24
GHX 117	27	18	25	15	15	1.87	7.08	4.0	30

to 30%. Langer et al. [65] have found that partial replacement of coarse AP by fine AP in RDX/GAP based aluminized compositions leads to improvement in velocity of detonation and to a decrease in impact, as well as sensitivity to friction (Table 23).

Recently, CL-20 has also found application as an explosive component of aluminized AP compositions for underwater explosions. Incorporation of CL-20 results in a remarkable increase in density and velocity of detonation, as compared to GAP based RDX/AP/Al compositions, due to inherent higher density and velocity of detonation, as well as improved oxygen balance of CL-20 proper (Table 24).

Aluminized NTO and HMX combination based plastic bonded explosive compositions with 10% Poly NitroMethyl Methyl Oxetane (PolyNIMMO) as a binder and 10% K-10 as an energetic plasticizer developed in UK are designated as CPX. CPX 458 offers superior velocity of detonation among the reported CPX compositions (Table 25).

4.5. Thermobaric PBX Compositions

Thermobaric (TB) compositions are aimed at generation of high overpressure in enclosed spaces, such as caves and bunkers, and are most suitable to modern warfare threats. In 2003, the Naval Surface Warfare Center Indian Head Division (NSWC IHD) and the Talley Defense Systems (TDS) worked together to develop solid TB compositions containing a moderate-to-high Al content for lightweight shoulder-launched penetrating or anti-cave warhead for the M72 LAW system [66]. Various compositions developed by NSWC-IHD with PBXIH-135 as the baseline composition are summarized in Table 26.

Hall and Knowlton [67] reported thermobaric compositions based on wax, HTPB, or GAP as a binder. The challenge of their study was to determine comparative TB characteristics for chosen composition in confined tests. They observed the highest impulse and average peak pressure for GAP based compositions. Ti/HTPB based compositions were found superior to the corresponding Al based compositions in terms of the average peak pressure and impulse. The researchers also studied compositions containing GAP in combination with propriety energetic plasticizers and achieved the average impulse up to 975 kPa $\cdot$ msec. Hall and Knowlton [67] reported gelled thermobaric compositions incorporating 60–70% Mg/Al/Ti/Zr as a fuel with 20–30% energetic liquid nitromethane (NM) and isopropyl nitrate (IPN). NM based compositions exhibited a higher impulse, as compared to IPN based compositions. AN/AP/HMX are also incorporated as oxidizer/energetic components. The researchers found compatibility for all the combinations. The best results were obtained with the 30/30/40 NM/Al/HMX combination in terms of the average peak pressure (0.5 MPa) and average impulse (802 kPa $\cdot$ msec).

CONCLUSIONS

Although the precise reaction of Al with detonation products is not understood fully to this day, it is widely accepted that the consumption of Al takes place over a longer time scale, as compared to TNT, RDX, or HMX. The investigation into the detonation performance of aluminized high explosive compositions [33] has revealed that the influence of Al on performance of the composition depends mainly on the nature of the high explosive and on the Al particle size. The Al consumed on the sonic (Chapman–Jouguet) surface can support the detonation front. The positive effect is observed for high explosives both with positive or negative oxygen balance, provided that there is a higher content of hydrogen and a lower content of carbon in a molecule [18]. Fine Al particles are expected to be consumed more rapidly in the CHNO reaction zone, as compared to larger particles. A tangible effect of the particle size of nanometric Al, however, can be revealed only if the time of Al interaction with detonation products is rather small. Many times contradictory results have been obtained. It has been observed that

TABLE 24

Explosive Properties of CL-20 Based Underwater Explosives [35]

Explosive	CL-20	Al	AP	GAP	ρ, g/cm^3	D, km/sec
GHX-106	27	30	25	18	1.95	6.87
GHX-107	22	35	25	18	1.96	6.58

TABLE 25

Characteristics of CPX Compositions

Explosive	NTO/HMX/Al	PolyNIMMO	K-10	ρ, g/cm^3	D, km/sec
CPX 450	40/20/20	10	10	—	—
CPX 455	40/20/20	10	10	—	—
CPX 458	30/30/20	10	10	1.85	7.68
CPX 459	20/40/20	10	10	1.86	7.76
CPX 460	27.5/27.5/25	10	10	1.88	6.42

TABLE 26

Explosive Compositions Developed at NSWC IHD

Explosive	Composition	ρ, g/cm^3
PBXIH-135	HMX/Al/HTPB	1.68
PBXIH-135EB	HMX/Al/PCP-TMETN	1.79
PBXIH-136	RDX/AP/Al/PCP-TMETN	2.03
HAS-4	HMX/Al/HTPB	1.65
HAS-4 EB	HMX/Al/PCP-TMETN	1.73
PBXIH-18	HMX/Al/Hytemp/DOA	1.92
PBXIH-18 mod. 1	HMX/Al/Hytemp/DOA	1.77
PBXIH-18 mod. 2	HMX/Al/Hytemp/DOA	1.84
Talley Mix 5672	Al/Zr/IPN/Ethyl Cellulose (32/40/26.75/1.25)	2.21

a decrease in Al particle size down to submicron and nanometric size is accompanied by a higher fraction of the oxide film (Al_2O_3) film on the Al particles, which may be responsible for decreased performance of Al in certain cases. Introduction of AP in aluminized PBX compositions led to bubble energies superior than that of HBX-3. The additional total energy derived from the oxygen content of AP entails a greater extent of the oxidation reaction enhancing the underwater and air-blast performance.

Castable PBX compositions with 97% of the theoretical density and solid loading of 87–88% have been realized. Introduction of EIDS opens a new avenue in PBX research and a possibility of achieving the objective of developing compositions with the hazard class 1.6 (insensitive munitions). The Indian Head of the U.S. defence has introduced a series of EIDS. I-RDX (“improved” RDX) is being investigated as a component of aluminized explosives to achieve improvement with respect to insensitivity. PBXIH-135 (HMX/Al/PU) is one of the best examples categorized under thermobaric (thermo means “high temperature” and baric means “high pressure”) warhead systems. These insensitive munitions can be used against tunnels, caves, bunkers, and hard surfaces. Supersonic missiles and bombfill of the General Purpose category (500 and 2000 pound) demand insensitive munitions. In general, all the military services are undertaking the task of replacing the existing TNT based main charges with insensitive explosives, mainly cast plastic bonded explosives with higher solid loading and better mechanical properties, as well as higher lethal performance. Efforts are on to develop explosive compositions based on insensitive explosives, such as FOX-7, which may proliferate to the aluminized class of explosives. HEMRL is also working in this direction. A series of aluminized PBX compositions have been evaluated and selected ones have been subjected to underwater testing.

REFERENCES

1. G. Roth, "Performance of explosives," German Patent No. 173327 (1900).
2. J. S. Gharia, B. K. Athawale, and P. D. Sathye, "HE composition for enhanced blast effect," in: *Proc. 1st Symp. on Warhead Technology*, TBRL, Chandigarh (1983), pp. 152–161.
3. A. Maranda, "Research on the process of detonation explosive of mixtures of the oxidiser fuel type containing Al powder," *Propell., Explos. Pyrotech.*, **15** (1990), pp. 161–165.
4. E. Anderson, "Explosive. Ch. 2," in: J. Carleone (ed.), *Progr. Astronaut. Aeronaut.*, Vol. 155: *Tactical Missile Warhead*, Amer. Inst. of Aeronautic and Astronautic, Washington (1993).
5. J. S. Gharia, B. K. Athawale, S. R. Visal, and V. V. Phadtare, "Effect of Al particle size and percentage on blast composition," in: *Proc. 1st Symp. on Warhead Technology*, TBRL, Chandigarh (1983), pp. 144–151.
6. E. Stromose and S. W. Eriksen, "Performance of high explosives in underwater application. Part 2: Aluminised explosives," *Propell., Explos., Pyrotech.*, **15**, 52–53 (1990).
7. T. Keicher, A. Happ, and A. Kretschmer, "Influence of Al/ammonium perchlorate on the performance of underwater explosives," *Propell., Explos., Pyrotech.*, **24**, 140–143 (1999).
8. L. S. Wise, "Effect of Al on the rate of detonation of TNT," Picatiny Arsenal Technical Report-1550, Dover (1945).
9. W. R. Tomlinson (Jr.), "Development of new high explosive filler for AP shot," Picatiny Arsenal Technical Report-1290, Dover (1943).
10. W. B. Kennedy, R. F. Arentzen, and C. W. Tait, "Survey of the performance of TNT/Al on the basis of air-blast pressure and impulse," Monthly Report No. AES-6, OSRD 649, Division 2, (25 Jan., 1945).
11. J. Akhavan, *The Chemistry of Explosives*, The Royal Society of Chemistry, Cambridge (2004).
12. D. L. Frost, S. Goroshin, R. Ripley, and Zhang Fan, "Effect of scale on the blast wave from a metallized explosive," in: *Proc. 13th Int. Detonation Symp.*, Norfolk (2006).
13. F. Volk, H. Barthelt, F. Schedlbauer, and J. Wagner, "Detonation products of insensitive cast high explosives," in: *Proc. 8th Symp.* (*Int.*) *on Detonation*, Albuquerque (1985), pp. 577–586.
14. G.Baudin and A. Bergues, "Reaction model for aluminised PBX applied to underwater explosion calculations," in: *Proc. 10th Int. Detonation Symp.*, Boston (1993), pp. 646–655.
15. P. J. Miller, C. D. Bedford, and J. J. Davis, "Effect of metal particle size on the detonation properties of various metallised explosives," in: *Proc. 11th Detonation* (*Int.*) *Symp.*, Snowmass, Colorado (1998), pp. 214–220.
16. "Encyclopedia of explosives and related items," Picatiny Arsenal Technical Report-2700, V. 9, Dover (1983). P. T-396.
17. R. L. Simpson, R. W. Swansiger, D. M. Hoffinan, et al., "Target penetrator explosive development: optimization of fragment, blast and survivability properties of explosives for hard target applications," in: *47th Annu. Bomb and Warhead Technical Meeting*, Los Alamos (1997).
18. J. D. Corley, "Fuzed insensitive general purpose bomb containing AFX-645," in: *Proc. Int. Symp. on Energetic Materials Technology*, Meeting No. 680 (Phoenix, September 24–27, 1995), American Defence Preparedness Association (1995), pp. 98–103.
19. T. S. Costain and R. V. Motto, "The sensitivity, performance and material properties of some high explosives formulations," Picatiny Arsenal Technical Report-4587. Dover (1973), pp. 50–51.
20. W. C. Tao, C. M. Tarver, J. W. Kury, et al., "Understanding composite explosive energetics: IV. Reaction flow modeling of Al reaction kinetics in PETN and TNT using normalized product equation of state," in: *Proc. 10th Int. Detonation Symp.*, Boston (1993), pp. 628–636.
21. P. Brosseau, "Nanometric Al in explosives," *Propell., Explos., Pyrotech.*, **27**, 300–306 (2002).
22. L. A. Roslund and N. L. Coleburn, "Hydrodynamic behavior of HBX-1 and equation of state of the detonation products below the Chapman–Jouguet state," Naval Ordinance Lab., White OAK, Maryland (1970).
23. L. A. Roslund and N. L. Coleburn, "Hydrodynamic behavior of HBX-1 and equation of state of the detonation products below the Chapman–Jouguet state," in: *Proc. 5th Symp.* (*Int.*) *on Detonation*, ACR. 1-84, Passadena (1970), pp. 523–532.
24. A. R. Clairmont, PBX's *in Large Navy Munitions Program*, Vol. 7: *Cylinder Expansion Testing*, Naval Surface Warfare Center, Tech. Report No. 80-43, Maryland (1988).

25. N. L. Coleburn and T. Liddiard, "Hugoniot equation of state of several unreacted explosives," *J. Chem. Phys.*, **44**, No. 5, 1929–1936 (1966).
26. T. N. Hall and J. R. Holden, "Navy explosives handbook, explosion effects and properties. Part III: Properties of explosives and explosive compositions," Naval Surface Warfare Center, MP 88-116, Dahegren, India (2000).
27. C. J. Anderson and P. Katsabanis, "Evaluation of heat of detonation, Final report," Mining Resource Engineering Limited, Prepared for Defence Research Establishment Valcartier, Kingston, Ontario, April (2000). .
28. C. J. Anderson and P. Katsabanis, "Heat of detonation: Part II, Final report," Mining Resource Engineering Limited, Prepared for Defence Research Establishment Valcartier, Kingston, Ontario, May (2001).
29. H. P. Dorsett, P. Brosseau, and M. D. Cliff, "The influence of ultrafine aluminium upon explosives detonation," in: *28th Int. Pyrotechnic Seminar*, Adelaide, South Australia (2001), pp. 239–244.
30. *Engineering Design Handbook: Explosives Series Properties of Military Interest*, Army Material Command, Pamphlet AMCP 706-177, Washington (1971), p. 193.
31. M. F. Gogulya, A. Yu. Dolgoborodov, M. A. Brazhnikov, and G. Baudin, "Detonation waves in HMX/Al mixtures (pressure and temperature measurement)," in: *Proc. 11th Int. Detonation Symp.*, Snowmass, Colorado (1998), pp. 979–988.
32. M. F. Gogulya, M. N. Makhov, A. Yu. Dolgoborodov, et al., "Mechanical sensitivity and detonation parameters of aluminized explosives," *Combust., Expl., Shock Waves*, **37**, No. 4, 445–457 (2004).
33. M. J. Stosz, "Development of new explosives for the US Navy," in: *13th Int. Annu. Conf. of ICT* (1982), pp. 257–275.
34. I. J. Lochert, R. M. Dexter, and B. L. Hamshere, "Evaluation of Australian RDX in PBXN-109," DSTO-TN-0440, Edinburgh, South Australia (2002).
35. T. Keicher, G. Langer, T. Rohe, et al., "Herstellung und Charakterisierung von Unterwasserpreng-stiffen," in: *Proc. 30th Int. Annu. Conf. of ICT* (1999), pp. 121-1–121-12.
36. P. Wanninger, "Empfindlichkeit von Explosivestoffen und Ladungen gegen Beschuss," in: *Proc. 22nd Int. Annu. Conf. of ICT* (1991), pp. 5-1–5-23.
37. E. Kleinschmidt, "Empfindliche Explosivstoffe — eine Getahr für die Umwelt?" in: *Proc. 24th Int. Annu. Conf. of ICT*, 26-1–26-24 (1993).
38. W. Arnold and H. Muthig, "KS22a, the insensitive high for hard target defeat applications," in: *Insensitive Munitions and Energetic Materials Technology Symp.*, Orlando (2003).
39. Vinay Prakash (Mrs), V. K. Phadke, R. K. Sinha, and H. Singh, "Influence of Al on performance of HTPB based aluminised PBXs," *Sci. Def. J.*, **54**, No. 4, 475–482 (2004).
40. F. Volk and F. Schedlbauer, "Detonation products of less sensitive high explosives formed under different pressures of argon and in vacuum," in: *Proc. 9th Symp. (Int.) Detonation*, Portland (1989), pp. 962–964.
41. P. A. Jemmett and N. Davies, "Mechanical and chemical characterisation of a polymer bonded explosive during aging," in: *Proc. 31st Int. Pyrotechnics Seminar*, Fort Collins, Colorado (2004), pp. 679–685.
42. P. Cheese, P. Barnes, M. Sharp, et al., "Studies on the effect of aging on a UK range of polymer bonded explosives," in: *Insensitive Munitions and Energetic Materials Symp.*, Event No. 5550, Hilston (2004).
43. Hui Huang and Haishan Dong, "Studies on low vulnerable high explosives," in: Chen Lang and Feng Changgen (eds.), *Theory and Practice Energetic Materials*, Proc. 4th Int. Autumn Seminar on Propellants, Explosives and Pyrotechnics, Sha oxing, China (2001), pp. 12–18.
44. S. K. Poehlein, D. Burch, R. Johnson, et al., "Requalification of demilitarized HMX for military use," in: *Proc. 36th Int. Annu. Conf. of ICT* (2005), pp. 8-1–8-13.
45. T. C. McGregor, K. A. Clark, M. Beyard, and K. Sandagger, "Requalification of demilitarized HMX for DOD/DOE applications," in: *Insensitive Munitions and Energetic Materials Technology Symp.*, Bristol (2006).
46. M. A. Radwan, "Explosive characteristics of aluminised plastic bonded explosives based on octogen and polyurethane binder," in: *32nd Int. Annu. Conf. ICT* (2001), pp. 44-1–44-9.
47. J.-S. Lee and C.-K. Hsu, "Thermal properties and shelf life of HMX–HTPB based plastic-bonded explosives," *Thermochim. Acta*, **393**, 153–156 (2002).
48. Hwu Wen-Hwa, Cheng Chin-Sheng, and Huang Chen-Chia, "Study on thermal decomposition of PCP/AP/RDX propellants," in: *Proc. 24th Int. Annu. Conf. of ICT* (1993), pp. 80-1–80-14.
49. B. S. Min, G. Baek, and S. W. Ko, "Characterization of polyether-type GAP and PEG blend matrices prepared with varying ratios of different curatives," *J. Ind. Eng. Chem.*, **13**, No. 3, 373–379 (2007).
50. W. H. Wilson, J. W. Forbes, P. K. Gustavson, and G. T. Sutherland, "Experimental study of detonation in PBXW-123, a large failure-diameter, non-ideal explosive," in: *Proc. 10th Int. Detonation Symp.*, Boston (1993), pp. 63–68.
51. P. Sjoberg, H. Hytti, R. Strandberg, A. Krariniemi, and M. Muilu, "PBX with insensitive RDX, a new EIDS substance for underwater use," in: *Proc. 33rd Int. Annu. Conf. of ICT* (2002), pp. 16-1–161-12.

52. J. W. Lec, J. Lee, J. H. Kuk, et al., “Air blast measurement of an aluminised explosive,” in: *Minutes of 25th Explosive Safety Seminar*, Vol. I, Anaheim (1992), pp. 429–451.
53. J. Mala, J. Groux, and Y. Bigot, “Detonation properties of insensitive cast PBX’s at low temperature,” in: *Proc. 11th Int. Detonation Symp.*, Snowmass (1998), pp. 384–390.
54. M. Held, “Steady state detonation velocity D_∞ of infinite radius derived from small samples,” *Propell., Explos. Pyrotech.*, **17**, No. 6, 275–277 (1992).
55. M. J. Stosz, “Advanced development of insensitive PBX’s for less vulnerable munitions,” in: *Minutes of 20th Explosive Safety Seminar*, Norfolk (1982), pp. 1165–1191.
56. G. Baudin and A. Bergues, “Reaction model for aluminised PBX applied to underwater explosion calculations,” in: *Proc. 10th Int. Detonation Symp.*, Boston (1993), pp. 646–655.
57. M. W. Smith and M. D. Cliff, “NTO-based explosive formulations: A technology review,” DSTO-TR-0796, Salisbury, South Australia (1999).
58. M. R. Senn, K. E. Newman, T. E. Wise, and W. S. Jones, “Chemicals and processing assessment of candidate explosives for the advanced bomb family,” IHTR-1370, Naval Ordnance Station (1990).
59. R. L. Spear, I. J. Dagley, and P. Whitty, “Options for future RAAF GP bombs meeting IM and/or HD 1.6 Criteria,” DSTO-CIC-0001, Aeronautical and Maritime Res. Lab., Melbourne, Australia (1994).
60. L. T. Wilson, D. R. Reedal, and B. M. Simpson, “Comparison of PBXW-126 and PBXC-129 for use in large fragmenting warheads,” in: *Insensitive Munitions and Energetic Materials Technology Symp.*, Event No. 854, National Defense Industrial Association (1997).
61. M. J. Murphy, R. L. Simpson, P. A. Urtiew, et al., “Reactive flow model development for PBXW-126 using modern nonlinear optimization methods,” in: S. C. Schmidt and W. C. Tao (eds.), *Topical Group on Shock Compression of Condensed Matter*, Conf. of the Amer. Phys. Soc. (Washington, August 13–18, 1995), AIP Press, New York (1995), pp. 417–420. (Am. Inst. of Phys. Conf. Proc.; Vol. 370.)
62. A. Be’cuwe, A. Delclos, and J. Isler, “EIDS high explosives for 1.6 munitions,” in: *Proc. Int. Symp. on Energetic Materials Technology*, Meeting No. 680, Am. Defence Preparedness Association, Phoenix (1995), pp. 119–124.
63. B. Nouguez, “Dual Formulation Warheads: A mature technology,” in: *Insensitive Munitions Technology Symp.*, Meeting No. 471, Am. Defence Preparedness Association, Virginia (1994), pp. 280–287.
64. J. Leathy, “PBXW-126, an insensitive explosive for general purpose bombs,” *ibid.*, pp. 517–523.
65. G. Langer, T. Keicher, W. Ehrhardt, et al., “The influence of particle size of AP and Al on the performances of underwater explosives,” in: *Proc. 34th Int. Annu. Conf. of ICT* (2003), pp. 12-1–12-16.
66. N. Johnson, P. Carpenter, K. Newman, et al., “Evaluation of explosive candidates for a thermobaric M72 law shoulder launched weapon,” in: NDIA 39*th Annu. Gun and Ammunition/Missiles and Rockets Conf.* (2004).
67. S. Hall and G. D. Knowlton, “Development, characterisation and testing of high blast thermobaric compositions,” in: *Proc. 31st Int. Pyrotech. Seminar*, Fort Collins (2004), pp. 663–678.