Thermobaric and Enhanced Blast Explosives – Properties and Testing Methods

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Abstract: The review of the available literature on thermobaric explosives and enhanced blast explosives (high-destructive explosives) is done in the paper. These types of explosives are defined, their common features and differences are shown. Special attention is paid to the physical phenomena accompanying the process of explosion of such fuel-enriched heterogeneous explosives. These materials are divided into liquid and solid mixtures and composite materials, including layered charges. The considered explosives are characterized in details, methods of determination of their blast parameters are discussed and the results of experimental tests are presented.

Keywords: Thermobaric explosives · Enhanced blast explosives · Blast waves · Testing methods

1 Introduction

Ideal molecular high explosives (HE) such as 2,4,6-trinitrotoluene (TNT), cyclo-1,3,5-trimethylene-2,4,6-trinitramine (RDX), pentaerythritol tetranitrate (PETN), and cyclotetramethylene tetranitramine (HMX) generate during detonation fast decaying blast waves of high peak pressure with very short duration and are designed to throw shrapnel, shatter structures or penetrate armors. However, they are lethal only within their immediate vicinity and show visible shortcomings for defeating hardened targets such as tunnels and caves. To overcome these shortcomings, great efforts have been focused on the development of new weapons able to generate higher impulse, higher blast and able to use its energy not to destroy corners or walls, but to travel around it efficiently and defeat hardened targets.

Scientists had obviously been attracted by the dramatic and devastating explosions recorded by the chemical, petrochemical, and food industry that do not directly involve explosives. For instance, wheat or soy flour may, if a critical concentration ratio flour/air is reached, form an explosive mixture and a spark is enough for initiation of its explosion. In such a manner accidents happen each year around the world. On the other hand, coal dust in mines could also generate the same type of explosions. In the early 1960s, scientists began experimenting with this concept to produce a weapon that uses the same principle, but employs volatile gases and finely powered explosives [1].

Thermobaric weapons have been part of that development. As the name suggests, they are optimized for the effects of heat and pressure, while the typical advancement of weapons focuses on achieving better results in fragmentation, penetration, and brisance. Thermobaric weapons are a subcomponent of a larger family of weapon systems commonly known as volumetric weapons. The characteristics of this weapon category are the creation of a large fireball and good blast performance [2].

Russia was the first to develop such kind of weapons. RPO-A Schmel rocket infantry flame thrower fielded in 1984 was the first successful thermobaric weapon, in which a self-deflagrating mixture made of magnesium (Mg) and isopropyl nitrate (IPN) was applied. This simple thermobaric explosive sent devastating pressure wave through the Afghanistan caves and tunnels system, giving a deep damage within the subterranean mazes [3].

Recent conflicts have seen increased use of thermobaric weapons. Russia has employed this type of weaponry extensively in Afghanistan and Chechnya [2], but this new class of energetic material did not receive extensive attention until March 5th, 2003, after U.S. Forces bombarding Gardez mountains, in eastern Afghanistan. This event was widely reported by the news media and the new term “thermobaric bomb” was used [1].

Recently, great efforts have been focused on the development of these weapons. The Russian formulation is effective, but not without problems. The liquid IPN is both volatile and detonable, and has been known to leak and spill, causing storage and toxicity problems. The US National Academy of Sciences has found that the fundamental physical phenomenon of thermobaric explosives should be rec-
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recognized to rapidly enforce the development of thermobaric weapons [4]. Thus, a lot of research studies have focused on the comprehension of thermobaric effects, in order to enhance or prevent them.

It is generally known that chemically active metals such as aluminum and magnesium are added to condensed explosives to increase the total energy liberated during the explosion. Although these metals do not react quickly enough to take part in the reactions in the detonation zone, they may react with the gaseous products of explosion or with oxygen from the surrounding air and significantly increase the strength of the blast wave. Comparison of the combustion energy of metals in air (20–30 kJ per gram of metal) with the detonation energy of classic explosives (6 kJ per gram of explosive) suggests that it is possible to significantly increase the effective energy delivered from the explosive charge, if burning of the metal particles is so programmed to proceed with adequate rate, then the energy released could strengthen the blast wave.

2 Thermobaric and Enhanced Blast Explosives

The property of an explosive to produce a blast wave is called the blast ability. The impact of blast wave can be further enhanced by debris (fragments) driven by the expanding detonation products. Thermobaric Explosives (TBX) or explosives with high-blast (Enhanced Blast Explosives, EBX) produce a long-lasting pressure wave with moderate intensity. The effects of explosion of such materials are more similar to the effects of detonation of the fuel-air mixtures (Fuel-Air Explosives, FAE) than those of ideal, condensed explosives. A characteristic feature of this type of explosives in the initial phase of the explosion is a phenomenon of dispersion of the detonation products and unreacted fuel to the surrounding air. In the next stages of the explosion, a mixture of fuel and oxygen from the air is spontaneously initiated to exothermic reaction which enhances the pressure wave. Even without debris, such a wave is a serious threat to humans.

The composition materials used in TBX and EBX explosives may consist of an explosive matrix and metal powders or other fuel, a binder, and an oxidant. Annual charges in the form of cylindrical layers containing these components are also used. The detonation of such explosives is accompanied by three stages of combustion [5]:

1. In the first stage, anaerobic (without participation of oxygen from air) reactions are present in the detonation wave and lasting a few microseconds. They are mainly redox reactions of explosive molecules. Phenomena in the detonation wave affect the crushing ability of explosive composition, such as the ability to destroy the casing.

2. Anaerobic combustion reactions, lasting hundreds of microseconds, are mainly the reactions of detonation products with fuel particles, too large to be burned in the detonation wave. Combustion reactions after the detonation affect the blast wave characteristics that determine the blasting capability of an explosive, i.e., the ability to break down the walls of buildings, bunkers, etc.

3. Last, aerobic (with oxygen from air) combustion stage takes tens of milliseconds and is carried out in the air and fuel-rich products after mixing them by the shock wave generated by the explosion and the accompanying turbulence. The main effect of afterburning process is heat, which raises the temperature and pressure of gases and strengthens the blast wave.

A review of the available literature shows that very often terms TBX and EBX are used interchangeably, as the phenomena accompanying their explosions are similar. However, EBX is primarily to strengthen the blast wave, while TBX is to increase in temperature and pressure of the explosion, the classification of charges to a specific type depends on how the fuel is burned after the ending of the detonation. In materials like EBX there is talk about anaerobic combustion reactions, or combustion without oxygen from the air. This means that after passing of the detonation wave, most of the fuel burns in the products of detonation. In materials like TBX, reactions of the fuel and oxygen from the air dominate [5, 6].

Explosives such as TBX and EBX can therefore provide a much higher total energy than conventional explosives. It should be pointed out that the main part of the additional energy is used to heat the gaseous medium and to strengthen the total pressure pulse of the blast wave, but this wave is still characterized by a relatively low amplitude (Figure 1). In the case of an internal detonation, multiple shock reflections enhance the afterburning reactions, generating high level of quasi-static pressure and substantial damage on the surrounding structures.

In recent years, scientists from various countries have conducted parallel researches on finding the solid explo-

![Figure 1. Pressure history inside the blast wave; high explosive vs. TBX and EBX detonations.](image-url)
sives, which would cause effects similar to the model liquid explosive (IPN/Mg) and on the development of tests to better characterization of the explosion phenomenon of such materials. In principle, first small scale tests are carried out, which allow roughly assessing the explosive composition in terms of its sensitivity and characteristics of the blast wave, and larger scale tests allow for subsequent selection of the components and the selection of the best composition in terms of blast capacity. Studies on the composition focus on several types of binders, various explosives, and metallic fuel, including the influence of the size and shape of the particles on the characteristics of the detonation, the process of particle dispersion, and blast wave parameters. The final composition must be a compromise between reaction rate, the optimal dispersion of fuel and non-oxidized detonation products and the ability to initiate combustion of the mixture of fuel and air. The explosion process must be sufficiently slow to disperse the fuel, but fast enough to guarantee that the combustion process is not interrupted. If the process is too fast then the fuel is too widely dispersed and heat density generated is too small to initiate the subsequent oxidation of the fuel particles.

3 Solid Explosive Mixtures

Mixtures of explosives with metal powders are classified as blast explosives due to the fact that an additional energy from the oxidation of the powders is released in the anaerobic stage and used mainly to strengthen the blast wave. Aluminum and magnesium are the most commonly used metals in this type of explosives.

In preliminary studies on the composition of solid TBXs the presence of metallic fuel and an explosive with an energetic binder was assumed in an explosive mixture. The authors of Ref. [3] were investigated just this type of composition by comparing initially its properties with the properties of the Russian reference material (IPN/Mg). Compositions were selected in such a way that large quantities of hydrogen and unreacted fuel were present in the products of detonation. In order to find the optimum composition, different high explosives including HMX, RDX, CL-20 (hexanitrotetranitromethane), TNT, (1,3,5-trinitrobenzene) and various types of metallic fuels of varying size and shape (nanocrystalline aluminum, aluminum spherical particles, flaked aluminum, alloy Mg/Al, metals Ti, B, Mg) were used. Cast and cured explosive compositions were selected to create the best composition. The binder and plasticizer were to replace the IPN to ensure a much lower sensitivity of the composition. Mixtures with additional oxidant were not studied in Ref. [3].

These studies were carried out according to standard methodology for blast explosives by increasing the scale of the experiment. In a small scale a 10-g sample was tested for sensitivity to friction, impact, electrostatic discharge, and heat (auto-ignition temperature). The mixtures with excessive sensitivity to any of the tested stimuli were not scaled up. The blast ability tests were carried out initially in a partially confined small bunker (about 15 m³ volume) using PCB pencil gages. The gages were placed outside the bunker at different distances from the charge. A pressure trace was measured by each gage, from which the impulse was calculated. In the next test, 500 g charge was placed in a two-chamber blockhouse. The rooms were connected by a doorway and each of them had an external doorway and a square window. The two-piece roof was designed to lift in a controlled manner, and the lift height was measured with a high speed camera. Moreover, the pressure was recorded using pressure sensors.

On the basis of the results of the experiments it was found that, for the high explosives, HMX was better than TNAZ or CL-20 and was comparable with RDX. As for metal powders, the best blast effects were obtained using powder of Mg/Al alloy. The Al/Mg alloy acts as a low-temperature initiator and it works better than boron or titanium. Moreover, flaked Al is better than spherical Al as regards the performance of the cast-cured explosives.

The relationship between the heat of combustion and the blast performance for aluminum containing explosives was studied in Ref. [7]. The study was conducted under the ground, in a closed chamber and in open space. First, underground tests were performed. The lifting height of a steel plate by a buried explosive charge was measured. Analysis of the plate height yields the heave energy. Four compositions were tested for various contents of high explosives, aluminum powder and a binder, and the explosion results were compared with the effect of Tritonal (TNT/Al 80/20). Then, tests were carried out in a closed chamber with a volume of approx. 100 m³. The pressure changes within the chamber were measured. For the experiments, five different types of PBX composition with aluminum powder were used and their effects were also compared to the performance of Tritonal. At the end, the investigations were conducted in the air. The same compositions were used as in tests in the closed chamber. The pressure history was measured at a certain distance from detonating explosive and the peak pressure and specific pulse of the blast wave were determined.

Based on the experimental results, the authors of Ref. [7] drew conclusions regarding the oxidation of the main elements contained in the studied explosives, such as aluminum, carbon, and hydrogen. The tested materials had an insufficient amount of oxygen required for complete oxidation of the fuel. The results of theoretical calculations for the explosives were helpful. On the basis of calculation results, it was found that there is a large difference in the heat of combustion by retained oxygen of tested explosives, if it is assumed that all elements react simultaneously (synchronous self-oxidation) and when a specific element reacts first in an order (asynchronous self-oxidation). For asynchronous self-oxidation, it was assumed that the reac-
tion proceeds in order of aluminum, carbon, and hydrogen. Taking into account the results of the underground tests, a correlation was found between the heat of combustion calculated for synchronous self-oxidation and the heat energy of tested explosives. This result might say that during the detonation of the aluminaized explosive firstly oxidation of carbon and hydrogen occurs at the detonation wave and next the oxygen contained in CO₂ and H₂O react with the aluminum under conditions of high pressure and temperature resulting in producing Al₂O₃. Aluminum may be a ruling component in this series of combustion process in conditions of oxygen deficit, even though exact reaction mechanism of aluminaized explosives is indistinct.

Quasi-static pressure (QSP) was determined by averaging the measured pressure signal in the closed chamber test, and extrapolating it back to time corresponding to the initiation of the detonator. A linear relationship between the QSP and the total heat of combustion of the explosives tested was found. Thus, it was concluded that during the confined explosion, in which there is sufficient amount of oxygen, complete oxidation of the fuel contained in the charge takes place.

Analysis of the data from the free explosions shows that there is no correlation between pressure pulse generated by the explosion and the total heat of combustion of the explosive. This means that the elements contained in the explosive do not burn completely, when the charge detonates in the unlimited space of the oxygen rich air. However, it has been found that the pressure pulse of blast wave is a function of the product of the heat asynchronous self-oxidation and the velocity of detonation raised to the power 2/3. The authors of Ref. [7] indicate that the blast pulse can be amplified when the rate of pressure increase due to the reaction of combustion is much greater than the rate of its decay caused by the rapid expansion of the explosion product.

The problem of the oxidizing component was raised in the study [8], in which the influence of a new type of oxidant in the PBX type composition on the blast performance was presented. Ammonium perchlorate (AP) is commonly used as an oxidizer because it has a positive oxygen balance and increases the heat of combustion through asynchronous self-oxidation. However, it causes an increase in the sensitivity of the explosive [9]. It was demonstrated in Ref. [8] that the use of an oxidant, called OX-A, in an amount of 20% resulted in a significantly lower impact sensitivity of the composition than the use of ammonium perchlorate, but also decreased the blast performance of the composition. The sensitivity was tested in an assay, wherein the sample of explosive composition was accelerated to a speed of 150 m s⁻¹ and it hit a steel plate. The authors showed that by using a mixture of oxidants OX-A and AP it was possible to create the explosive composition which was low-sensitive to impact and had a good blast performance.

The study of detonation and blast characteristics of compositions consisting of explosives, aluminum powders, or other additives were also conducted in Refs. [10–13]. Research on the effect of aluminum contents (15–60%) and its particle form (powder with a size below 74 μm and flaked Al) on detonation characteristics of RDX-based compositions was carried out in Ref. [10]. Tested explosive mixtures were made from RDX phlegmated by wax (RDXₚₚ) and aluminum. Measurements of detonation velocity for different charge diameters and confinements were performed. The shock curvatures of the detonation wave for unconfined charges and charges confined with a water envelope were measured by applying X-ray photography. The acceleration ability and energetic characteristics of the detonation products of the mixtures were determined from the cylinder test results. From the data of the cylinder tests it follows that aluminum particles take part in reactions with gaseous detonation products and the amount of aluminum, which has reacted must be considerable because the acceleration ability of the detonation products of the RDX-based explosive with 30% aluminum is evidently greater than in the case of the mixture containing 30% LiF (inert).

Research on the same compositions containing phlegmated RDX and aluminum were continued in Ref. [11]. In this paper, the authors focused on the phenomena accompanying the explosion in an open space (air) and in closed chambers. Parameters of blast waves in the air were measured by the use of piezoelectric gauges. Simultaneously, photodiode set-ups were used to measure light output of the detonating charges. Quasi-static pressure measurements were conducted in steel chamber of 0.15 and 7 m³ volume filled with air. Moreover, the heat of detonation was measured with a calorimetric bomb.

From the results of measurements of the free explosions, it was found that the overpressure peak of incident wave for tested aluminaized explosives was comparable or lower than that of recorded for pure phlegmated RDX. However, an increase in the impulse was observed. The time duration of light generated by the detonation products of aluminaized explosives were longer than that measured for RDXₚₚ. This means that aluminum particles react with the gaseous products and air during their expansion. From the tests performed in the steel chamber it followed that the values of QSP for the aluminaized RDX-based explosives were higher than those for the pure RDXₚₚ. It was proved that the reaction of aluminum particles with oxygen from air and detonation products took place in the chambers. The maximum heat of detonation measured in the calorimetric bomb filled with argon corresponded to an aluminum contents of 30% for both the aluminum types.

Continuation of Refs. [10, 11] is Ref. [12] concerning the non-ideal explosives based on RDX. Charges of phlegmated RDX containing 30% of two types of aluminum particles (an average size of 5 and 90 μm), coarse aluminum oxide and fine lithium fluoride particles were tested. The re-
search concerning influence of inert and reactive additives on the detonation velocity and QSP was carried out. To estimate the degree of combustion of reactive particles, closed explosions were performed in a chamber filled with different gases. Explosion residues were also analyzed.

From comparison of the experimental detonation velocities with those obtained from thermochemical calculations it followed that both aluminum powders behaved in the reaction zone like chemically inert admixtures. The QSP measured in the 0.15 m³ chamber for the mixtures containing fine particle size aluminum was slightly higher than that of compositions with coarse aluminum. The QSP for the mixtures with inert additives was much lower than that obtained for the mixtures with aluminum. Thermogravimetric curves indicated that chamber residues after detonation the RDX₄₉/Al charges in air contained entirely aluminum oxide. When detonation took place in nitrogen or argon atmosphere chamber residue contained aluminum oxide, aluminum nitrate, carbon, and metallic aluminum.

The influence of gaseous atmosphere on the afterburning of detonation products of the same RDX-based explosives was also investigated in Ref. [13]. Heats of explosion were measured in four various atmospheres (argon, nitrogen, air and argon/oxygen mixture) at a pressure of 2 MPa. Calculated detonation energy and calorimetric heat measured in an atmosphere without oxygen were in quite good agreement for the mixtures containing inert additives. But calorimetric heat measured for the RDX₄₉-aluminum mixtures in similar conditions was greater than the detonation energy calculated for the compositions containing inert additives. It was proved that about 50% of aluminum mass was burnt inside the bomb filled with argon or nitrogen. The presence of oxygen in the compressed gas filling a bomb led to complete combustion of the detonation products and aluminum particles.

Small charges of aluminized RDX-based plastic explosives were studied in Ref. [6] for the effect of particle size and ambient gas on the blast performance. From the tests performed it followed that aluminum particles in the 3–40 μm range provide primary blast enhancement. The blast driving reaction is approximately 50% aerobic and 50% anaerobic. Full oxidation of aluminum within 10 microns was observed in tests in a closed chamber filled with air. In the absence of external oxygen, the aluminum is typically oxidized only to the 50% level, except for the smallest particle size tested (3 μm) where nearly full oxidation was stated.

HMX-based cast-cured formulations were tested in Ref. [14] in a series cylinder and plate-pushing experiments. Inert lithium fluoride powder was substitute for aluminum powder in the explosive. In cylinder tests, no significant difference was observed in the detonation velocities between the aluminum- and LiF-containing formulations, and measured cylinder wall velocities for HMX-Al and HMX-LiF were identical at 1 μs. However, at 2 μs, wall velocity was 13% higher for HMX-Al explosive, and increased to 20% at 20 μs. Measured plate velocities at a timescale 100–200 μs were up to 31% higher for HMX-Al than for HMX-LiF. Free field pressure measurements show 38% higher pressures for HMX-Al.

Blast performances of pressed and cast HMX-based plastic bonded explosives (PBX) were compared in Ref. [15]. Free-field pressure and quasi-static overpressure in a blast chamber were measured. The experimental results show that the pressed aluminized explosives yielded higher initial air-blast performance than the cast-cured explosives. However, the cast-cured explosives provided higher internal blast performance in the chamber.

Alloys of aluminum and magnesium are often used to increase the blast performance of explosives. In Ref. [16], the effect of Al₃, Mgₙ alloy content on the detonation and blast characteristics of the phlegmatized RDX-based compositions was analyzed. Measurements of the detonation velocity, QSP, and heat of detonation were done. The results obtained were similar to those for the compositions with aluminum [12,13].

Investigation of blast parameters of mixtures of explosive oxidizer and fuel were conducted in Ref. [17], where the characteristics of blast waves generated by the charges containing mixture of ammonium nitrate (AN) and powdered aluminum (Al) were measured. Flaked aluminum or powder of aluminum were used in charges with contents 10% and 40% by weight. It was demonstrated that the blast wave peak measured for AN/Al charges is lower than that for phlegmatized RDX charges of the same mass. However, the overpressure impulses are comparable and even larger for the AN/Al compositions.

Boron [18–21], magnesium [18–20,22], titanium [18–20,23] and their alloys [18–20] are other metal powders used in explosives in order to increase their blast performance. Silicon was investigated in Ref. [24] as a possible replacement of aluminum. The detonation performance of explosives with and without Si was tested using a plate dent test and a cylinder test. The detonation velocity and pressure of the RDX-Si explosive were below that of the comparison formulations based on RDX or HMX. From the cylinder test data and thermochemical calculation it follows that nearly 80% of the silicon reacts by 7 volume expansion of the reaction products.

To investigate the phenomena accompanying the detonation of explosives containing metal powders, experimental methods are used to measure the intensity of light emitted from the explosion cloud and its temperature. Photodiodes are usually used to measure the light output and temperature of expanding gaseous products [11,25–28]. A double-wavelength Si-Ge photodiode was used in Refs. [25,26] to determine temperature-time histories after detonation of TNT- and RDX-based explosives. It was proved that thermobaric charge based on RDX, isopropyl nitrate and aluminum is more effective than TNT charge in potential thermal action.

The fireball temperature histories corresponding to the detonation of homogeneous charges and heterogeneous
charges were determined in Ref. [27] using three-color optical pyrometry assisted by qualitative spectroscopy. For metalized explosives, asymptotic temperature values were reached (after tens milliseconds) that were consistently 700-800 K higher than the corresponding temperatures from fireballs from baseline homogeneous explosives. In some cases, explosively dispersed metallic particle ignite only after some delay time. In this case, optical pyrometry can be used to estimate the ignition delay time of the metal particles.

High speed spectroscopy and two-color pyrometry was used in Ref. [28] to measure the light intensity and temperature of the explosion cloud after detonation of aluminized explosives. The aim of this work was to improve the understanding of the combustion of metal particles dispersed by heterogeneous explosive mixtures. It was proved that depending on particle size and environmental geometry, the combustion occurs with variable delays and at non-monotonous rates, with reflected shock waves enhancing the reaction by compressing and mixing the reactants.

High brightness imaging (HBI) was used in Ref. [29] to study the structure of the leading shock, particles immediately behind the shock, and the following boundary of the fireball produced during testing of EBXs. The HBI Technique employs a high powered, high repetition rate copper vapor laser synchronized to a filtered high speed camera. The laser illuminates the fireball with light (510 nm) that is usually much brighter than light emitted by the fireball. A special optical system was used to obtain sharp images throughout the period of the explosion. Results from a series of measurements on several conventional and enhanced blast explosives showed significant difference in separation between leading edges of shock and fireball. For certain EBXs, the gap between the leading shock wave and the fireball appears to contain small particle. For the formulations that show particles in the gap, the fireball velocity and gap distance is up to twice as large as for other formulations. According to the authors of Ref. [29], the presence of particles ahead the fireball is indicative of increased turbulent mixing within the fireball, increasing the blast effect.

4 Liquid Explosive Mixtures

Liquid thermobaric explosives, which include liquid fuel, are similar to fuel air explosives (FAE). However, a FAE spreads almost 100% of the energy at the aerodynamic stage of the explosion while a TBX release this energy in the three stages of explosion. Solid thermobarics release about 2/3 to 3/4 of the energy in the initial and anaerobic stages, while liquid thermobaric explosives output about 1/3 to 1/2 of their energy in these stages leaving the rest for aerobic combustion. Exothermically decomposable liquid fuel mixed with a powdered metal, usually 40-75% by weight, are dispersed by a spreading explosive charge of mass of 10-20% related to total weight of composition [5]. In the case of this type of formulations the highest energy density is achieved as they contain more fuel than other explosives. In addition to this type of thermobaric charges, different types of mixtures of liquid explosives with metal powders were investigated in the literature.

In Ref. [5] the authors tried to compare solid explosive mixtures with IPN-based liquid compositions by determining TNT equivalents for them. The study used a spherical liquid fuel charges and a spreading internal charge of plastic PETN. IPN was used as the basic fuel, and tests were performed with mixtures of IPN with 2-ethylhexyl nitrate and IPN with diesel fuel. As a solid fuel, powders of magnesium, aluminum, and aluminum activated with fluoride or nickel were used. In addition, elektron (an alloy of magnesiu, aluminum and zinc), charcoal, powdered red phosphorus, and amorphous boron were used. Metal powder and fuel were pumped to the interior of the spherical charge. The reference explosive was a 1 kg sphere made of cast TNT and a detonator of pressed TNT placed inside it. Measurements were carried out in the open air. The charges were suspended at a height of 12 m above the ground. Pressure sensors are mounted on the three different distances.

Based on the performed experiments, it was found that for the thermobaric explosion the ignition occurs after mixing of the fuel with the surrounding air and begins in the outer part of the gas cloud. As a result, a phenomenon of implosion occurs which closes the cloud, and eventually generates a high, prolonged pressure inside the cloud. To occur the implosion effect, the powdered metal should have a structure delaying the ignition, and also should quickly burn up. The metal powder should not substantially react in the anaerobic stage, but in the aerobic step it should be easy ignited. It has been found that activated aluminum is the best for this purpose. It was also found that magnesium burns too quickly in the anaerobic phase and does not require large amounts of oxygen, which results in a very short duration of the pressure pulse. In contrast, ordinary aluminum does not ignite unless it is very fine, but in this case it combusted very rapidly and leads to strengthening of the shock wave in the anaerobic step instead of producing a long lasting pressure pulse.

In Ref. [26] a number of attempts have been made to reveal the differences between a standard charge of TNT and hybrid aluminized explosive called RISAL. The latter belongs to the thermobaric explosives and is a mixture of 53% liquid isopropyl nitrate, 29% RDX powder, 14.5% flaked aluminum, and 3.5% silica. Weight of the cylindrical charges of TNT and RISAL was 1 kg. The study was carried out in the open space and in a concrete building of 200 m³ volume. The blast wave parameters were measured by specially designed sensors and the radiant heat flux and temperature of the expanding detonation products were measured using double-wavelength photodetectors. The results
of pressure measurements in the open air showed that the pressure peaks from the detonation of RISAL mixture at a distance of 2.5 m were about 1.5 times higher than the peaks from the TNT charges, but these differences disappeared with increasing distance. Similar trend was observed when the positive phase pulses were compared. Thus, from the pressure measurements two conclusions are drawn. Firstly, it was found that at close distances (1–3 m from a 1 kg charge) RISAL mixture had better blast performance (demolition ability) than TNT. Second, the pressure equivalent of RISAL is not fixed, and decreases with increasing distance.

In the case of explosion in the building, the peak pressure measured at a distance of 3 m from the charge was also higher for RISAL. The distinguishing feature of an explosion in the building is the appearance of a number of pressure peaks after approximately 10 ms from the moment of reaching the sensor by the incident shock wave. The results allowed the authors to conclude that the tested charges had much greater demolition ability in the closed facility than in the open air.

Enhanced blast explosives that consist of a mixture of reactive metal particles with a liquid explosive have also been investigated over the past decades. To discover the process of explosion of liquid explosives containing metal particles, it is important to know the critical conditions for the initiation of the particles in a laboratory scale and during the explosion in a field scale. Such a purpose had research undertaken by the authors of Ref. [30]. Packed beds of magnesium particles saturated with nitromethane (NM) sensitized with 10% by weight triethylamine (TEA) were tested in a field scale. The blast wave overpressure was recorded with piezoelectric pressure transducer located at different distances. The particle dispersion and ignition were monitored using two high-speed video recorders. During the explosive dispersion of the magnesium particles, one of three different events was observed: (1) prompt ignition of particles, (2) delayed ignition of particles at a point within the dispersed particles cloud, or (3) no ignition of the particles. The blast wave parameters in the case of delayed or no ignition were considerably lower than in the case of prompt ignition of the particles.

For spherical charges, the experiments showed that a critical particle size (between 85 and 240 μm) exists for prompt particle ignition for charges with a diameter of 12.3 cm or less. The critical charge diameter for particle ignition (CDPI) is a strong function of particle size. While a charge diameter of about 3 cm is sufficient for the prompt ignition of 85 μm particles, for 240 μm particles a charge diameter of 21.5 cm is required. For smaller charges, particle ignition may occur after a delay of several milliseconds, but in this case, the particle combustion is not sufficiently rapid to augment the strength of the blast wave [30]. For cylindrical charges in glass tubes, the critical charge diameters for prompt ignition of the 85 μm particles is between 18 and 25 mm, whereas for 240 μm particles it is above 49 mm.

The critical conditions for the ignition of spherical aluminum particles dispersed during the detonation of cylindrical explosive charges were investigated experimentally in Ref. [31]. The charges consisted of packed beds of spherical aluminum particles (size from 3 to 114 μm in diameter) saturated with liquid NM sensitized by TEA. The charges were placed inside 122 cm long glass tubes with various inner diameters. A high-speed camera, a 3-color pyrometer, and a line spectrometer were used in field scale experiments. The existence of a CDPI was the subject of Ref. [31] for charges containing aluminum. The CDPI was found to be a strong function of particle size. The CDPI for a long cylindrical charges displays a U-shaped curve at the particle diameter–charge diameter plane with the minimum CDPI corresponding to 50 μm particles. With increasing charge diameter, three particle reaction regimes were observed: (1) sub-critical (no dispersed particle ignition), (2) near critical (discontinuous reaction of the expending particle cloud), and (3) supercritical (rapid continuous reaction of the particle cloud).

The effect of various physical scales on the blast wave from metalized explosives consisting of packed beds of magnesium or aluminum particles saturated with liquid mixture of nitromethane and TEA was investigated in Ref. [32]. The results of measurements of the shock wave parameters (peak and impulse pressure) were shown in the graphs as a function of relative distance from the center of the charge, i.e., a distance related to the characteristic radius, the value of which is proportional to the cube root of the energy released in the explosion (the sum of the explosion energy of nitromethane and the energy of complete combustion of a metal powder). In the case of magnesium powder having a diameter of 85 μm, which reacted promptly for all charge sizes, the dependence of the peak or impulse on the relative distance can be described by a single curve for all applied charge masses (with the exception of the impulse of the shock wave generated by the largest charge containing 5.5 kg of powder Mg). If particles with 240 μm diameter were used, the largest peak and pulse were recorded for the blast wave produced by the largest charge containing the mass of 12 kg Mg. In this case, the peak and pulse values were similar to those obtained for the charges containing 85 μm particles.

The influence of metal casing on the ignition and reaction of aluminum particles from the detonation of cylindrical charges consisted of packed beds of aluminum and liquid NM sensitized by TEA was investigated in Ref. [33]. Three types of casing were used: 2.1 mm wall steel tubes and aluminum tubes with wall thickness of 2.1 or 6.35 mm. Three particle reaction regimes were also observed for charges with metal casing. Unlike the U-shaped function of the CDPI vs. particle diameter previously observed in glass tubes [31], the small particles (ca. 13 μm) are more readily to ignite and react in steel and aluminum tubes. Conse-
quently, the CDPI becomes a monotonic increasing function with an increase in particle diameter in the range of 10–110 μm. The ignition delay for the dispersing particles was evaluated to be 13–18 μs for 13 μm particles and 30–63 μs for 54 μm particles in metal tubes. At the supercritical particle reaction regime, the casing fragments sizes are smaller and the blast become stronger compared with the results obtained from the near-critical particle reaction regime.

Ref. [34] is devoted to the study of changes in pressure on a wall during the reflection of the blast wave after the explosion of heterogeneous charges containing packed beds of metal particles saturated with liquid NM sensitized with TEA. Active and inert metal particles were used in the charges. The results for the heterogeneous compositions were compared with those obtained after the explosion of a charge of homogeneous explosive C4. Tested cylindrical charge was placed at a distance of about 10 charge diameters from the center of a vertical plate. Six piezoelectric sensors shielded by silicone coating to protect them from the effects of the hot products explosion were installed on the plate. Expansion of the particles was recorded using a high-speed video camera.

The measurement results revealed that the process of detonation of a metalized explosive carried out near a rigid surface can lead to the strengthening of the force acting on the surface in comparison to the case of a homogeneous explosive. The reflected pressure and impulse, normalized with the incident values, for aluminized explosives containing particles of various average diameters, were less or equal to the corresponding values for homogeneous C4. In contrast, charges containing higher density reactive metal particles (irregularly shaped higher density reactive metal – HDRM) produced a significantly enhanced normalized reflected impulse at the surface.

Similar problems of interaction of a heterogeneous explosive blast with a single wall were analyzed theoretically in Ref. [35]. The sensitized NM/Al explosive was used in numerical simulations. Hybrid kinetic-diffusion aluminum reaction model, aerodynamic breakup of liquid metal droplets and wall impact fragmentation of particles were the subject of that study. In conclusion, the authors have stated that outstanding differences between the numerical model and experiment imply further investigation.

The burning rates of aluminum particles in the detonation products of nitromethane were assessed on the basis of the results of cylinder tests in Refs. [36, 37]. Mixtures of nitromethane gelled with 3 wt-% polymethylmethacrylate (PMMA) and 5 μm Al powder or nanophase Al powders were investigated. Mass fraction of Al was 20% or 40%. Initially, nanophase aluminum powders were thought to be useful to enhance the ballistic capability of explosives. However, the cylinder test results show similar efficiency for 5 μm and nanometric Al particles. Comparing to gelled NM ballistic efficiency, 20 wt-% of Al additives increase the efficiency as soon as the beginning of the copper tube accelerating, 40 wt-% of Al powders increase the efficiency only after 22 μs of tube acceleration. Authors of Ref. [37] carried out cylinder tests on NM/Al compositions containing 20, 30, 40, 50 and 60 wt-% spherical aluminum particles with a mean size of 10.5 μm. Nitromethane was thickened by 5% wt. polyethylene. By comparing modeling with experimental cylinder test data the authors found that the burn time for 10.5-μm Al particles was longer than the detonation transit time for a standard cylinder test (typically 50 μs).

Investigation of detonation parameters, blast wave characteristics and quasi-static pressures (QSPs) for mixtures of nitromethane gelled with 4 wt-% PMMA and particles of an aluminum and magnesium (Al, Mg) alloy was carried out in Ref. [38]. The mixtures of gelled nitromethane containing 15, 30, 45 and 60 wt-% Al-Mg alloy were tested. Detonation velocity and Guerney energy were determined. Parameters of blast waves produced by charges of the investigated explosives were measured. thermochemical and gasdynamical calculations were also performed. The comparison of the experimental and theoretical values of the detonation velocity indicates that the Al-Mg alloy behaves as an inert component and the temperatures of detonation products and solid particles are not equal in the detonation reaction zone. This conclusion confirms similar inferences presented in many papers devoted to the mixtures of nitromethane with aluminum or magnesium particles. The ballistic capability of the explosives containing 15 and 30% Al-Mg alloy is comparable and even greater than that estimated for gelled nitromethane without the additive. From the comparison of the measured and calculated velocities of the copper tube it follows that aluminum and magnesium react with the detonation products during the tube expansion, i.e., within the time period of 20–40 μs.

The overpressure peak and specific impulse of the tested mixtures containing the Al-Mg alloy are greater than that of gelled nitromethane. The greatest increase in the blast parameters is observed for the mixtures with 30 and 45% additive. From tests performed in a closed chamber, it follows that the values of QSP for the mixtures containing the alloy are higher than those for pure gelled nitromethane.

5 Composite Explosives and Layered Charges

A separate group of explosives with enhanced combustion efficiency and improved blast parameters are composite and layered explosives. The composite materials consist of large macroscopic particles composed of a binder, a reactive metal, and an oxidizer. In the layered charges, these components are present in the form of cylindrical layers.

The invention proposed in Ref. [39] involves a new class of composite, solid explosives or energetic formulations. Instead of the traditional method of consolidating microscopic particles of energetic materials, metal powders, and binder, these new composite solid materials are formulated.
by consolidating macroscopic fragments, each fragment being itself a complete shock-insensitive energetic formulation, comprising a number of microscopic particles of energetic materials, metal fuel, and binder. Explosive compositions exposed to a weak shock wave fragment and burn instead of detonate, but the detonation process occurs if they are loaded by a strong shock wave. Also munitions built from these materials became the object of the patent claim, in particular, thermobaric charges.

Pressable explosive compositions are claimed in patent [40], which include at least 40% of substantially uncoated fuel particles, a nitramine mechanically blended with the substantially uncoated fuel particles, and a binder coating the nitramine. The invention presented in Ref. [41] concerns coated fuel particles, which have a magnesium core and an aluminum coating. Upon detonation, the nitramine disperses the coated fuel particles over a blast area during a first overpressure stage. The aluminum coating of fuel particles is stoichiometrically less than the amount of ambient-air oxygen available in the blast area for aerobic combustion with aluminum. Once exposed, the magnesium cores may combust to increase the impulse generated in the first overpressure stage. Other composite explosive material is disclosed in patent [42] which has a detonable energetic material dispersed within a high-explosive composition. The energetic material has at least one layer composed of a reducing material and at least one layer composed of a metal oxide. This composite explosive enables to manipulate the burn rate of fuels in the explosive to enhance their lethal contribution in a thermobaric weapon by optimizing the overpressure vs. time behavior of the resulting blast.

High performance aluminized explosive compositions for high performance, high blast, low sensitivity explosive applications are disclosed in Ref. [20]. The composition comprises an explosive ingredient (Cl-20, HMX, RDX, or another material), a binder, and aluminum powder. The explosive is preferably pressable and mixable to permit formation into grains. According to the authors of patent [20], the aluminum fully participates in the detonation of the explosive, manifesting its energy into metal pushing energy. The aluminum is substantially reacted at two volume expansion of the expanding gas, and fully reacted prior to seven volume expansion.

Layered explosive charges were described in U.S. patents [18,19], in which metatized compositions comprising a reactive metal, oxidizer, and binder, and optionally a plasticizer and a catalyst were also the patent subject. So-called SFAE charges (Solid Fuel - Air Explosive) were patented, i.e., a solid fuel-containing charge of an annual design, and their new explosion properties were claimed. The SFAE charge may be selected from the group consisting of reactive metal and metal composite. Such charges offer increased thermal effect of the explosion and are able to produce a relatively high pressure (200–400 kPa) lasting longer than 50 ms in environments conducive to a rapid decline in temperature (free explosion). They are also able to maintain high pressure in a long time in a confined volume with limited amount of oxygen. This type of explosives is characterized by increased reactivity and thermal output and lower ignition temperature [19].

The metallic composition may be produced in two ways. In the first one, the metal powder is coated by a polymer and pressed. Thus prepared composition can be used in warheads with a cylindrical explosive charge in the form of PBX comprising HMX, RDX, or the CL-20. In the second method, the metallic composition is prepared by mixing, casting, and curing of metal powder or metal/oxidizer powder with an explosive in order to produce castable PBX's.

Detonation properties of the metallic composites in the listed patents were only described without giving the results of research. In the literature, there are few works on testing the performances and the blast ability of such composites and SFAE charges.

Comprehensive laboratory studies of SDF (Shock–Disperse–Fuel) charges are presented in Ref. [43]. Such charges may be included in SFAE-type charges. The SDF charge consisted of a spherical booster charge of 0.5 g PETN, embedded in a paper cylinder of approximately 2.2 cm³, which was filled with powdered fuel compositions. The compositions contained aluminum powder, hydrocarbon powders like polyethylene or sucrose, and carbon particles. These charges were studied in three different chambers of 4-dm³, 6.6-dm³, and 40.5-dm³ volume and the small-scale model of a closed tunnel section. A high speed video camera was used to monitor the combustion. In addition, a number of piezoelectric pressure gages in the chamber wall measured the transient and quasi-static overpressures.

The experiments described in Ref. [43] show that shock dispersed fuels are most effective in narrow confinements, where shock reverberations enhance the mixing between fuel and air. The largest effects were observed for fuels that contain aluminum flakes. Larger confinement in some cases caused a failure to ignite the fuel. However, aluminum flakes or mixture of aluminum flakes and sucrose yielded overpressure levels close to the theoretical limit even in the 40.5-dm³ vessel.

FAE type devices in much greater scale were tested in Ref. [44]. The test charge consisted of 1.13 kg spherical C4 core surrounded by 1.92 kg of aluminum flakes. The study was aimed to measure the characteristics of the blast in two partially enclosed areas, verification of computer code SHAMRC for fluid dynamics modeling and estimation of the amount of energy released in the combustion process.

The tests were carried out in two rooms. The rooms were labeled as the source room and the adjacent room, with the inside volume of 52 m³ for each room. Each room had an exterior doorway covered with responding wooden doors and an external open window. Pressure gauges were placed in the walls and ceilings of both rooms and dynamic pressure was measured between the two rooms.
measurements included the dynamic pressure between the two rooms and the temperature. Pressure measurements indicated the existence of three phases on the time history of the pressure. The first pressure peak reaches a gauge located on the wall near the door in the source room at about 3 ms from the initiation of the explosion, followed by a stronger shock reflected from the nearest wall at around 5 ms. The second group of pressure peaks and the third group come back to the gauge at around 11 ms and 17 ms, respectively, after blast waves' reverberations in the room. It appears that the strength of the blast waves decreases in time, even though the aluminum still burns. After the third phase (approx. 20 ms), only random small pressure peaks at the level of the noise are observed. Therefore, if the first two stronger shocks do not inflict damage to the target, a third or subsequent weaker shocks are not expected to do much more. In other words, afterburning reactions occurring during the first 15–20 ms are much more important from the point of view of the blast capability of explosive charge than those occurring later.

From detailed analysis of the results obtained by using the numerical code SHAMRC with the experimental results it was found, that there are some differences in the pressure histories that may result from assumptions in the calculation of a greater degree of conversion of aluminum than it is in reality. Calculations show that about 70% of the aluminum is consumed in 15 ms after detonation and 97% to 75 ms. Inefficient mixing of aluminum particles with oxygen in the air may be responsible for a relatively long reaction time. The measurement results suggest that the blast properties of this type of SDF mixtures are not as good as assumed and is not much better than the properties of typical thermobaric explosives, such as TBX A (the composition of this explosive is not given). Although the blast efficiency of the tested SDF charges is about 10% higher at 50 ms than that of the TBX A charge of the same mass, during the first 15 ms, when the blast effects are the most important, the SDF charge is in fact about 10% less efficient than TBX A. This is due the fact that proportionally more energy is released in the SDF charge after the blast-effective time scales than in TBX A [44].

The explosion of an annular charge composed of a phlegmatized RDX (RDXph) core and a layer consisting of a mixture of ammonium nitrate (AN) and aluminum (Al) particles was studied [45,46]. X-ray photography was used to trace the curvature of the shock wave in the external layer. It was found that the external layer is compressed and dispersed by the shock wave and the expanding detonation products of the internal explosive charge. It appears that the detonation phenomenon does not occur in the external layer.

The pressure blast characteristics and the light output of the explosion cloud were also investigated using bunkers of different sizes and varying levels of the opening. Overpressure peaks, the impulses of incident waves, and the impulses determined for specified time duration were analyzed. The measured blast wave characteristics and the light outputs of explosion clouds confirm the ammonium nitrate decomposition and aluminum particle combustion during the explosion. The size of the used phlegmatized RDX core only slightly influences the aluminum combustion process after detonation of the layered charges in the bunkers. However, this influence can be observed in charges having the highest aluminum content (75%) in the mixture with ammonium nitrate in the external layer. The ratio of the charge mass to the bunker volume influences the aluminum oxidation process. It was proved that oxygen from air is used for aluminum particle combustion during the late stage of particle dispersion.

The confined explosion of layered charges composed of the RDXph core and an external layer of aluminum powder or a mixture of ammonium perchlorate (AP) and Al (25/75 or 50/50) was studied [47,48]. Two types of aluminum powder (particle sizes below 44 µm or between 44 and 149 µm) were used in the mixtures. Experiments were carried out in fully and partially closed structures, i.e., in the explosion chamber of 150 dm³ in volume and in the 40 m³ volume bunker with four small holes and a doorway. The charges used in research in the bunker had 246 and 462 g weight. Pressure and light histories were recorded in the bunker. Charges of 40 g weight were used in the explosion chamber. Signals of overpressure from two piezoelectric gauges located at the chamber wall were recorded and a quasi-static pressure determined. Moreover, the solid residues from the chamber were analyzed by using SEM, TG/DTA, and XRD techniques to determine their structure and composition.

From the analysis of the results obtained for the bunker it follows that the parameters of the incident blast wave increased by only 25–30% after the explosion of the larger layered charges despite the fact that the charge weight increased twice. The blast wave parameters grow up with the increase of aluminum contents, particularly in the case of charges with larger diameter core. This means that aluminum burns, and additional heat strengthens the blast wave already during the detonation products expansion. The increase in the total pressure impulse in the bunker, determined for the time of about 40 ms, for almost all large charges is 80–100% in relation to charges weighing less than twice. The highest values were obtained for charges with the outer layer of pure-aluminum powder. Light output time of explosion of the layered charges is 3–4 times longer than the RDXph core.

Analysis of the results obtained for the chamber leads to conclusion that the application of the outer layer in the RDXph core causes twofold increase in quasi-static pressure inside the chamber filled with air. The values of a ratio of the QSP to the average pressure obtained from thermochemical calculation show that only part of the aluminum burns up during the measurement time of overpressure in the chamber (40 ms). Lack of oxygen from air causes that
the QSP in the chamber filled with argon decreases with increasing AI contents in mixtures with AP. From the TG/DTA and XRD analysis of the chamber residue it follows that the aluminum powder is almost completely burned after the explosion of the layered charges. But metallic aluminum is present in the residue after detonation of charges with Al and AP/Al 25/75 in the chamber filled with argon.

The problem of dispersion and ignition of metal particles by the detonation products in thermobaric charges is crucial regarding the effectiveness of such charges and has already been extensively studied. The rapid dispersal of inert solid particles due to the detonation of a heterogeneous explosive, consisting of a packed bed of steel beads saturated with liquid explosives, was investigated experimentally and numerically in Ref. [49]. The results indicate that, when the detonation reaches the surface, the frontal particles rapidly accelerate within a distance of the order of the charge diameter to a terminal velocity. The particles velocity is roughly constant and the inertia of the particles allows them to penetrate through the detonation products, and to overtake the decelerating, diverting primary shock wave.

The behavior of solid particles dispersed by high explosive was investigated in Ref. [50]. Spherical charges made of a 125 g C4 explosive surrounded by inert (glass spheres) or reactive particles (aluminum particles and flaked aluminum, magnesium particles) were detonated in a free field area. The total mass of particles inside the casing ranged from 330 g to 470 g for the smaller casings and from 750 to 1100 g for the bigger ones. Visualization of the explosion process was performed with a high rate video camera. Images were processes by modified Schlieren method. Blocks of wax were used to capture the dispersed particles and to analyze qualitatively and quantitatively their state after interaction with the shock wave. The experimental results revealed that aluminum particles form relatively big agglomerates, many of them having a diameter larger than 3 mm. Those agglomerates seem incompletely reacted. Examination of glass particles reveals that most of them were broken into fragments. Because of the agglomeration and combustion phenomena, it is impossible to conclude whether the aluminum particles were broken or not. The results of pressure measurement revealed that particle bundles moving in front of the blast wave induce pressure disturbances when passing nearby the pressure gauges.

The investigation of aluminum particles dispersion by high explosive was continued in Ref. [51]. For all aluminum particles types (5, 45, 100, and 200 μm average diameter), the expanding fireball is the first phenomenon observed on the high speed images during the first 500 μs. As the detonation products decelerate with the distance from the charge center, the fireball edge is at first overtaken by aluminum agglomerates crossing the field of view at approx. 1000 m s⁻¹ for all four tests. After the additional 500 μs, it becomes possible to visually separate the leading shock from aluminum particles. The resulting velocity of the first agglomerates and the velocity of the leading shock are only marginally different between the 5 μm and the 200 μm particles.

A special particle trap (disk) connected with a rotating slit was used in Ref. [51] to collect particles at known times of arrival. The arrival times of 5 μm and 45 μm particles determined by the optical method and the trap were in good agreement at the 1.2 m distance. The main difference between the 45 μm and the 5 μm dispersion was observed to lie in the density of particles on the disk surface – more particles were collected for the 45 μm dispersion. According to the authors of Ref. [51] this can be explained by the fact that the smaller particles decelerate faster and their consequent flight distance is shorter and smaller particles are burnt during the test due to the higher reactivity of them.

The phenomenon of jet formation during explosive particle dispersal was investigated experimentally and numerically in Refs. [52–54]. Solid particles can be dispersed explosively in two configurations: (i) a uniform mixture of the particles with the explosive, or (ii) a layered arrangement with particles surrounding an explosive charge. During particles dispersion, in both cases, instabilities often cause the formation of particle clustering leading to jet-like structures. High-speed cameras were used to observe formation and propagation of the jetting fireball. The photographs connected with numerical simulation of clustering and jetting of particles made it possible to explain phenomena of creating instabilities on the surface of the expanding cloud of detonation products and the growth of jets of particles [54]. The formation of jets of hot reactive metal particles after detonation of thermobaric charges has a significant influence on the efficiency of combustion of the particles in oxygen from the surrounding air.

6 Conclusions

Thermobaric explosives (TBX) and enhanced blast explosives (EBX) constitute a sub-family of volumetric weapons. They are fuel-enriched heterogeneous explosives. Unlike ideal high explosives, they are designed to produce a long-lasting pressure wave able to travel along corridors, propagate around corners and through obstacles. They are extremely effective and destructive in enclosed spaces due to their ability to produce a high level of quasi-static pressure (QSP). A much higher total energy is provided by TBX and EBX explosion comparing to conventional explosives. This energy may significantly strengthen the generated blast wave and/or magnify the explosion fireball and the resulting thermal effect. A good recipe for a TBX or EBX composition could consist of an explosive matrix and a metal powder or other fuel, a binder, and an oxidant. Composites in form of macroscopic energetic granules containing these components are also used.

TBX and EBX be divided to solid explosive mixtures, liquid explosive mixtures, and the very promising compo-
site and layered charges. The current state of research and features of each type are thoroughly described in this paper. Differences between TBX and EBX are usually small and therefore often these two names are used interchangeably. However, EBX are primarily to strengthen the blast wave, while TBX are to increase temperature and pressure of the explosion. Anaerobic and aerobic reactions occur both in EBX and TBX. But in EBX formulation, the metallic fuel reacts mostly in the anaerobic stage without participation of the oxygen from air, resulting in an important energy liberation which participate in the sustaining of the initial blast wave and impulse, while in TBX, the aerobic metallic reactions dominate and the liberated combustion energy gives rise to a moderate pressure and high temperature after the detachment of the shock wave, relatively for a long time in the last stage of the explosion. If the fundamental physical and chemical phenomena of TBX and EBX can be understood and consistently controlled, a new weapons system of significant efficiency or series of weapons systems may become available to the warfighter in the future.

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