Full Paper

Propellants,
Explosives,
Pyrotechnics

DOI: 10.1002/prep.202000103

Performance of Magnesium, Mg-Al Alloy and Silicon in Thermobaric Explosives – A Comparison to Aluminium

Stanisław Cudziło,*[a] Waldemar A. Trzciński,[a] Józef Paszula,[a] Mateusz Szala,[a] and Zbigniew Chyłek[a]

Abstract: A direct comparison is made between the effectiveness of Al, Mg, their alloy (Al_3Mg_4), and Si powders as additional fuels in explosives using the thermobaric effect. The experiment produced calorimetric measurements of the detonation heat and a record of the overpressure histories which were used to determine the quasistatic pressure (*QSP*) in an explosion chamber after the detonation of charges from mixtures containing 30 % fuel and 70 % RDX passivated with wax. The measured heat values indicate that Al–Mg alloy is a more effective additional fuel during anaerobic post-detonation reactions than Al and Mg separately. Silicon also exothermically reacts with the detonation products, but the released heat only compensates for the lower amount of RDX in the charge. Similar to the calorimetric measurements, the lowest value of *QSP* was obtained for the mixture with Si powder. In contrast to anaerobic conditions, silicon proved to be an equally effective thermobaric additive as Al, Mg, and Al–Mg powders in air explosions.

Keywords: Thermobaric explosives · Metallic additives · Detonation heat · Confined explosion parameters

1 Introduction

Modern thermobaric explosives (TBXs) are almost without exception compositions containing high-energy explosive (usually RDX or HMX) metal powders, an additional oxidant (usually ammonium perchlorate, AP), and a binder (wax or a polymer with the addition of plasticizer) [1–6]. Only metals with high combustion enthalpy are of interest as potential components of TBX, with the most important of these being aluminium. Aluminized explosives have been widely used for over 100 years [1]. The flagship representatives of these explosives are Tritonal (80 % TNT, 20 % flaked Al); TGAF-5 (40 % TNT, 40 % RDX, 20 % Al) Torpex (42 % RDX, 40 % TNT, 18 % Al); Dentex (48.5 % RDX, 33.5 % TNT, 18 % Al, 0.5 % wax). The potential energy content of the explosives cannot be fully converted to blast impulse, owing to poor combustion efficiency of Al, that is caused by alumina coatings on the Al particles and the lack of reactive oxidizers in the expanding detonation products. Addressing the latter drawback, additional oxidizers are incorporated in modern aluminized plastic-bonded explosives (Al-PBX), like PBXW-126 (22 % NTO, 20 % RDX, 20 % AP, 26 % Al, 12 % PU), PBXIH-135 EB (42 % HMX, 33 % Al, 25 % Trimethylolethane trinitrate/ Poly(caprolactone)), and AFX757 (25 % RDX/HTPB, 30 % AP, 33 % Al, 12 % HTPB) [1-3]. Contents of about 30 % aluminium and the simultaneous presence of AP identify them as thermobaric explosives. In charges with a density of approx. 1.83 g/cm^3, these explosives detonate at a velocity of 6450 m/s (PBXW-126); 7060 m/s (PBXIH-135 EB), and 6000 m/s (AFX-757). The TNT equivalent of these explosives is 1.10, 1.17, and 1.84, respectively, although researchers [1,2] have suggested that, in a confined space, the thermobaric performance of large charges can be more than twice as high as a TNT charge of identical mass. PBXIH-135 EB is also a low-sensitivity explosive and can be used in warheads of supersonic rockets, penetrating bombs, and artillery shells. This type of ammunition is effective against bunkers, tunnels, caves, and hard surfaces [3].

Thus, modern TBXs still contain aluminium powders, even though their disadvantages have long been known. The most important drawback is the high melting point of alumina (2040 °C) and even higher boiling point of metallic aluminium (2467 °C). Permanent Al_2O_3 layers covering particles or droplets of aluminium impede their ignition, slow down the combustion process, and, as a consequence, cause incomplete utilization of the energy potential during the explosion of the TBX charge, especially when the explosion is in an open space. Under these conditions, the temperature in the explosion products (fireball) drops too quickly, and the surface oxidation processes of liquid aluminium cannot continue until atmospheric oxygen appears inside the post-explosion cloud.

The search for other elements, widely described in the available literature [6], that could replace aluminium (at least in part) in TBX compositions has not had great success, primarily due to the low reactivity and relatively low values of their heat of combustion (Table 1).

---

[a] *S. Cudziło, W. A. Trzciński, J. Paszula, M. Szala, Z. Chyłek*
Military University of Technology
Faculty of Advanced Technology and Chemistry
Kaliskiego 2
Warsaw 00 908 (Poland)
**e-mail: stanislaw.cudzilo@wat.edu.pl*

Table 1. Gravimetric and volumetric heat of combustion of additional fuels in TBXs [7,8].

Element	Heat of combustion, Q [kJ/g]	 [kJ/cm^3]
Boron	59.08	136.40
Titanium	19.71	88.68
Aluminium	31.00	83.71
Zirconium	12.01	77.93
Silicon	32.30	75.27
Red Phosphorus	24.68	53.31
Magnesium	24.73	43.03

From a practical point of view, boron is the only additional fuel in TBX that has a greater value of both gravimetric and volumetric heat of combustion than aluminium. Unfortunately, elemental boron has the same disadvantages that hinder the initiation and complete burning of aluminium particles in the expanding detonation products of condensed explosives. Boron's melting point is 2300 °C and boiling point is 3658 °C. Thus, boron particles only burn on the surface, remaining constantly in the solid phase. In addition, they quickly become covered with a layer of liquid boron oxide, which further hinders the access of gaseous oxidants to the combustion surface [6].

Schaefer and Nicolich [9] compared the parameters of blast waves generated in a partially confined space by the detonation of charges from PBX-type compositions containing HMX/Al–Mg/HTPB and HMX/Al–Mg/B/HTPB. Replacing a part of the aluminium-magnesium alloy (Al–Mg) with boron powder resulted in a nearly double reduction in the impulse of the air shock wave. The authors suggest that the long ignition delay of boron particles in detonation products makes this additive act as if it were completely chemically inert. They also conclude that until chemical or physical means of lowering the boron ignition temperature are found, the energy potential of this fuel cannot be fully utilized. Recently (2019), it has been proposed that magnesium hydride be used as a boron activator; however, the addition of these two fuels deteriorates the blast effect compared with the addition of standard aluminized explosive. Only the heat of detonation increased slightly (by about 1.5 %) [10].

Koch et al. [11] confirmed the usefulness of red phosphorus as a source of energy released by the expanding detonation products of RDX. The pressure in the blast wave in a confined space, generated by the explosive charge with an RDX/P = 70/30 mixture, was higher by approx. 30 % than the value measured after the explosion with an identical RDX/Al charge. This was attributed to the high reactivity of phosphorus and its easy availability in reactions with gaseous oxidants, resulting from its low boiling point (280 °C). Unfortunately, open space tests failed to confirm the advantage of red phosphorus over standard aluminium powder. A similar result was also obtained by Hahma et al. [12]. In a comparison of the characteristics of the blast wave in an open space between the explosion of isopropyl nitrate/red phosphorus (IPN/P = 26/74) and that of isopropyl nitrate/surface-activated aluminium mixtures (IPN/AAl = 39/61, particles coated with AlF_3 or nickel), the latter compositions were found to be superior. If the risks posed by red phosphorus and the low chemical and physical stability of redox mixtures containing phosphorus are taken into account, then phosphorus should be considered as a low-perspective additive to TBX.

A mixture of zirconium flakes and magnesium powder have also been tried in TBX with a liquid explosive (IPN) [13]. The results of blast wave measurements have not been published, but the authors of the cited work unequivocally stated that these metallic additives are only slightly better than aluminium powders from the energy point of view, while they are worse in terms of availability, price, and safety. Fine zirconium powders can spontaneously ignite in air, are extremely sensitive to electric spark, and increase the sensitivity of explosives to shock waves [6]. Zirconium and titanium in various forms (sponge compacted with a binder, pressed powders) have also been proposed as materials for incendiary or fragmentation-incendiary ammunitions. In a typical configuration, the cylindrical shells of these metals are driven by the detonation products of high explosives. Zirconium was proven to be the best material for such ammunitions, as its fragments were found to ignite in air and pierce the walls of the objects being attacked, causing great damage [14,15], but these are not applications that fall within the primary theme of this paper.

Of the seven elements listed in Table 1, only silicon and magnesium remain as prospective TBX components. The possibility of using the former in its elemental form in TBX compositions seems unlikely for the same reasons that aluminium and boron are unsuitable. Silicon melts at 1410 °C and boils at 2355 °C. Its combustion in expanding detonation products can, therefore, take place only in the condensed phase, and this, as has been emphasized, means low availability in reactions with gaseous oxidants. For that reason, the possible beneficial effects of silicon on thermobaric performance will only become apparent during the aerobic stage of explosion. However, it would be necessary to bridge the gap between microsecond detonation reactions and millisecond burning reactions by using another reactive additive at the same time. In that case, burning in the anaerobic stage would ensure the maintenance of a high enough temperature that the explosion products would mix with air.

In the available literature, the application of silicon and its compounds or alloys in TBXs is rarely mentioned [16]. In that research, an RDX-based silicon explosive (RDX/Binder/Si = 79/9/12) was developed and silicon reaction rate with RDX detonation products was studied using 2,54 cm copper cylinder expansion test and detonation calorimetry in an anaerobic environment. Both the methods indicated nearly 90 % silicon reaction (particles at a size of approx. 15 μm) to silicon dioxide based on the energy output of the tested samples and the results of XRD analyses of the detonation residue from the shots in the calorimetric bomb. This means that under the experimental conditions, silicon was capable of producing usable energy during expansion of detonation products of high explosive at early timeframes (within the first 15 μs of expansion, which equates to about 7 volume expansions) [16].

The use of magnesium as an additional fuel in TBX is as important as the use of aluminium. Historically, magnesium has overtaken aluminium in these applications. The first composition investigated, fully deserving of the term thermobaric, was a suspension of magnesium powder in isopropyl nitrate (IPN) gelled with nitrocellulose [1–6,17,18]. It is believed that the advantage of IPN is the high reactivity of its detonation products (with the presence of hydrogen and a high concentration of free radicals), guaranteeing the self-ignition of combustible explosion products after mixing with air. The choice of magnesium over aluminium was not accidental, either. Aluminium and magnesium have a very similar melting point (660 °C and 649 °C), whereas they differ significantly in boiling point (2467 °C and 1090 °C). Magnesium oxide, like alumina, melts at a very high temperature (3260 °C), but at 1090 °C, the MgO layers that previously covered magnesium droplets cease to act as a barrier to gaseous oxidants, since magnesium becomes part of this phase. Metals that boil at a temperature below the melting point of their oxides are said to meet the Glassman criterion [19]. In the fireball, their oxidation occurs mainly under homogeneous conditions, and this promotes the full use of the reaction heat to strengthen both destruction factors of thermobaric weapons (pressure and temperature). Such is the case even when small charges detonate and/or in a situation of limited atmospheric oxygen availability, e.g. when the explosion occurs in a narrow tunnel or a closed room with a small cubature.

To summarize, magnesium seems to be a good choice when it is necessary to maximize the parameters of the TBX anaerobic explosion stage, while the choice of aluminium (or other less reactive additive, e.g., B, Si) is justified when it is necessary to generate long-lasting, extensive pressure and temperature fields. Then, the combustion of a significant part of the metallic additive should take place in atmospheric oxygen. Moreover, Al can react exothermically not only with carbon oxides, water and oxygen but also with nitrogen to form aluminium nitride: $2Al + N_2 \rightarrow 2AlN +$ 346 kJ/mole [1]. However, for this to be possible, the anaerobic stage must be sufficiently energetic. This is achieved by using complex (multi-component) fuels. One of the newer versions of the Russian IPN/Mg composition combines the advantages of magnesium and aluminium. RISAL–P has the following composition: 51 % IPN, 28 % RDX, 14 % Al, 4 % Mg, 1 % Zr, and 2 % NC [2]. It can be assumed that RDX also plays the role of an additional aluminium activator in this composition.

This paper directly compares the effectiveness of aluminium, magnesium, their alloy (Al_3Mg_4), and silicon as additive fuels in explosives generating a thermobaric effect. Calorimetric measurements of the heat of detonation were performed under identical conditions, and the overpressure histories in the explosion chamber were measured after detonation of 50 g charges using mixtures composed of 30 % powders from these fuels and 70 % RDX passivated with wax.

2 Experimental

2.1 Materials

The tested explosive mixtures were composed of 70 % commercial grade RDX passivated with 6 % of wax (RDXph) and 30 % aluminium (Al), magnesium (Mg), aluminium-magnesium alloy (Al–Mg), or silicon (Si) powders.

Al and Mg powders were purchased from Alfa-Aesar (catalog numbers 11067 and 10233, respectively). They had purity higher than 99.5 % and particle sizes less than 43 μm (325 mesh). Silicon was in the form of 325-mesh powder with purity above 99 %. It is produced by ABCR GmbH (catalog number AB121855). Al–Mg alloy powder (Al/Mg molar ratio of approx. 3/4) with particle sizes below 45 μm was bought from an Internet source (pyrogarage.pl). The purity of the product was not specified by the supplier, but the results of thermogravimetric analysis proved that it was not less than 99 %. The active metal content was estimated by measuring the mass increase of the alloy sample with the elemental composition of Al_3Mg_4, after heating it on a thermobalance in an aerobic environment to completely oxidise the metals to their oxides.

All the powdery additives were used as obtained. Their morphology was determined by applying scanning electron microscopy (SEM) and infrared particle sizer (IPS). The specific surface area was also measured using a Micromeritics ASAP 2020 device. The measurements were carried out at the temperature of liquid nitrogen (−195.8 °C). Krypton of a purity 99.9999 % was used as an adsorbate. The process for measuring the specific surface area of all of the samples was identical and was performed as follows: a vial with a prepared sample was placed in the analytical port, and a measurement of the free space was taken by means of helium of purity 99.9999 %. For each sample, 10 measurements in the P/P_0 range from 0.02 to 0.3 in intervals of 0.02 were obtained (P/P_0 is the ratio of the current pressure P to the pressure at saturation at the temperature of liquid nitrogen P_0; for Kr, $P_0 = 0.3$ kPa). Brunauer-Emmett-Teller (BET) theory was used to describe the physical adsorption on a solid surface, and this served as the basis for the analysis and measurement of the specific surface area of the tested samples.

SEM images of Al, Al–Mg, Mg, and Si powders are shown in Figure 1. The photographs were taken at a magnification of 1000. The size distribution parameters of the powders and the final results of the BET analysis are given in Tables 2 and 3.

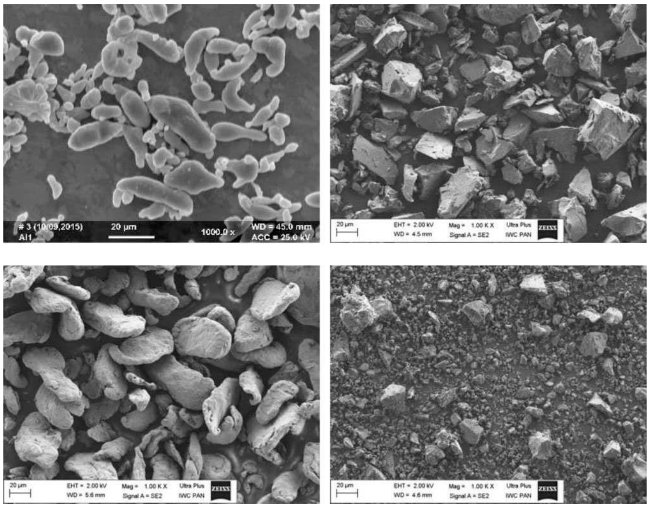


Figure 1. Top: SEM images of Al (left) and Al–Mg (right) particles. Bottom: SEM images of Mg (left) and Si (right) particles.

Table 2. Size distribution parameters of the powders.

Powder	Number distribution		Mass distribution	
	D_{med} [µm]	D_{mod} [µm]	D_{med} [µm]	D_{mod} [µm]
Al	8.4 ± 0.2	7.5 ± 0.6	15.4 ± 0.1	12.5 ± 0.3
Al–Mg	7.7 ± 0.2	7.1 ± 0.3	18.2 ± 0.3	14.6 ± 0.1
Mg	9.3 ± 0.1	7.1 ± 0.3	19.6 ± 0.5	18.1 ± 0.9
Si	6.3 ± 0.2	5.8 ± 0.6	16.3 ± 3.4	13.8 ± 4.5

Table 3. Values of the specific surface area of the powders.

Powder	Specific area BET [m^2/g]	Correlation factor
Al	0.4600 ± 0.0080	0.9993
Al–Mg	0.3898 ± 0.0150	0.9941
Mg	0.6846 ± 0.0120	0.9987
Si	0.9867 ± 0.0070	0.9998

Al particles are elongated with an oval shape. Their longer side is smaller than approx. 45 µm. Magnesium powder particles are oval and appear as several µm thick flakes of 10 to 50 µm in length and width. Most of them are compact and have a smooth surface, but some of the largest ones are fractured. Al–Mg powder is produced by grinding, and therefore its particles have irregular polyhedron shapes with sharp edges of approx. 10 µm to 40 µm in length. Si crystals are also very irregular in shape with comparatively wide size distribution, and there is a large predominance of particles below 10–20 µm in size. The sparse large crystals (above 30 µm) are covered with much smaller silicon particles, forming dendritic systems.

The particle size distributions, measured with IPS, were used to calculate the median diameter, D_{med} (the value of the central element in the distribution), and the dominant diameter, D_{mod} (the most frequent value of particle diameter). The average distribution parameters are presented in Table 2.

The additional fuel powders have a similar size distribution, and their particle sizes are in accordance with the declaration of suppliers (particle size less than 45 µm). Thus, the effect of particle size of the additives on the explosion parameters of the tested mixtures should be the same.

As shown in Table 3, silicon powder has the largest specific surface area (0.99 m^2/g), and the Al–Mg powder has the smallest one (0.39 m^2/g). These specific surface areas of 0.4 to 1.0 m^2/g are typical for powders with 325 mesh particle size; thus, the particles of tested powders do not have open pores on the surface. This conclusion is also consistent with SEM observation results (Figure 1).

The samples of RDX/wax/additive mixtures were prepared by granulation of RDXph/additive mixture in the presence of hexane. Hexane was used to permanently bind the additive fuel particles with RDXph particles, as it partly dissolves wax layers. The ingredients, taken in a designed ratio, were first dry mixed by hand in a container. After obtaining an optically homogeneous mixture, hexane was poured into the container, and the resulting putty-like substance was kneaded/rubbed to obtain a powdery consistency. The mixture was then left for 12 hours at ambient temperature for the solvent to completely evaporate.

For the calorimeter experiments, the powdery samples were pressed (at 300 MPa) into 25 g cylinder pellets of 25 mm diameter. The charges were weighed and measured to calculate their density. The measurements were performed twice, one hour and eighteen hours after production of the pellets. Results were identical and are shown in Table 4.

The charges used in the explosion chamber experiments had 50 g mass and a 30 mm diameter. They were pressed under the same conditions as described above. A set of the charges containing Al–Mg powder at 30 % loading is shown in Figure 2.

By visual inspection, the charges are mechanically strong, and their density changes from approx. 1.66 g/cm^3 for pure RDXph to 1.86 g/cm^3 for RDXph/Al = 70/30.

Table 4. Composition and density of the tested charges.

Explosive	Average density [g/cm^3]	Standard deviation
RDXph	1.655	0.003
+ 30 % Al	1.860	0.002
+ 30 % Al–Mg	1.727	0.001
+ 30 % Mg	1.663	0.002
+ 30 % Si	1.725	0.001

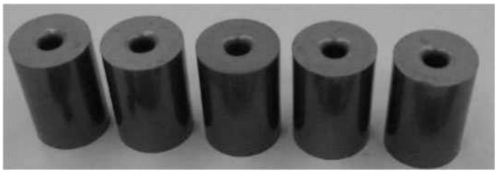


Figure 2. 50 g charges of RDXph/Al–Mg.

2.2 Calorimetric Measurements

A spherical steel bomb with an internal volume of 5.6 dm^3 was the main element of a water calorimeter used for the measurements. The bomb was placed in a polished stainless-steel calorimeter bucket that held 27000 ± 1 g of water. The bucket was surrounded by a constant-temperature jacket whose temperature was maintained at 20.0 ± 0.1 °C. The thermal equivalent of the instrument, determined by burning certified samples of benzoic acid with purified oxygen at a pressure of 2.0 MPa, was found to be 163.7 ± 1.2 kJ/K. This error of ±0.73 % indicates the ultimate precision of the instrument.

The 25 g charges were detonated in the calorimetric bomb filled with argon at a pressure of 2.0 MPa. Standard military detonators were used to ignite detonation. The detonator was made of primary and secondary explosives closed in an aluminium cup of approx. 1.6 g in mass. To estimate the energy released by the fuse, TNT charges of different masses were detonated in the bomb filled with argon. Assuming that the detonation heat of the fuse does not depend on the mass of the TNT charge (i.e. the degree of reaction of aluminium and the detonator explosion products with the gaseous products of TNT are independent of TNT mass), the dependence of the total heat effect on the TNT mass should be linear. This assumption enabled us to determine that the heat released by the fuse was 11.7 ± 0.45 kJ [20]. To calculate the detonation heat of an explosive, the difference between the measured total heat effect and the heat released by the fuse was divided by the mass of the tested charge. At least three measurements were performed for each explosive.

2.3 Pressure History Measurements

Pressure history measurements were performed in a 0.15 m^3 explosion chamber. The chamber was filled with air or argon at a pressure of 0.1 MPa. The charge was hung in the centre of the chamber, and standard military detonators were used to detonate the charges. To produce a pure argon atmosphere, the chamber was pressurized with argon up to 0.25 MPa and emptied three times. After the last filling to a pressure of 0.1 MPa, the chamber was ready for tests. In both atmospheres, air and argon, at least five tests were performed for each investigated charge. Overpressure signals from two piezoelectric gauges (PCB Piezotronics, model 102B) located at the chamber wall were recorded by a digital storage scope. Descriptions of the explosion chamber, measurement system, and data processing methods are provided in detail in our previous papers [21,22].

3 Results and Discussion

3.1 Detonation Heat Results

If any of the three first detonation heat measurements differed from the arithmetic mean by more than 4 %, two consecutive measurements were performed. The lowest and highest values were omitted, and the remaining three were averaged and rounded to the nearest ten. Results of the detonation heat measurements are shown in Table 5.

A composition containing 30 % Al–Mg produces approx. 53 % more energy during detonation in the calorimetric bomb than passivated RDX itself. This composition performs even better than aluminium and magnesium as a supplementary fuel in anaerobic post-detonation reactions. This can be a result of the fact that AlMg alloy melts at a lower temperature than pure Al and Mg by approx. 200 °C (463 °C for Al_3Mg_4, 660 °C for Al). Consequently, it begins to react with RDX detonation products at a lower temperature, and its burning efficiency in detonation products of RDX is greater than that of Al and Mg powders separately.

Magnesium meets the Glassman criterion for vapour phase combustion, so it should be more easily available for the reactions with RDX detonation products; nonetheless, the measured RDXph/Mg detonation heat is a bit lower than that of RDXph/Al. This is a result of the differences in combustion heat of the two metals (31,00 kJ/g for Al versus 24,73 kJ/g for Mg). The heat of reaction of aluminium with nitrogen also contributes to the measured heat effect. As a consequence, the additional energy release compensates for the lower availability of aluminium for combustion in RDX detonation products.

Silicon powder also partly burns during detonation of RDXph/Si in the calorimetric bomb filled with argon; however, in terms of energy efficiency, it is significantly behind other tested metallic fuels. Anderson et al. [16] estimated (experimentally and computationally) that even 89 % of Si

Table 5. Average detonation calorimetry results in 2 MPa argon atmosphere.

Explosive	Average detonation heat [J/g]	Standard deviation	Energy contribution [J/g]
RDXph	4990	70	–
+30 % Al	7190	70	3700
+30 % Al–Mg	7640	70	4150
+30 % Mg	7050	100	3560
+30 % Si	5130	40	1640

© 2020 Wiley-VCH GmbH

with a similar particle size reacts with the detonation products of RDX under the conditions of the cylinder expansion test and in the calorimetric bomb. The reason for the observed lower conversion of silicon may be a different quantitative composition of the tested explosives (only 12% of Si) and other conditions of calorimetric measurement (15 g sample of the tested explosives detonated using a 5.0 g C4 booster in an alumina crucible having a 0.25 cm thick wall [16]).

The difference between the experimental detonation heat of a mixture and the heat of detonation of RDX itself (3490 J/g that is 70% out of 4990 J/g) constitutes the energy contribution of the additive reactions with RDX detonation products. The calculated values are presented in the last column in Table 5.

Among the tested additives, Al–Mg powder is the most reactive in anaerobic combustion in the calorimetric bomb. Therefore, it is particularly preferable to sustain early metal reactions in the expanding detonation products and thus support complete burning of other less combustible components.

3.2 Quasi-Static Pressure Results

Eight overpressure profiles were recorded for each of the tested compositions both in argon and air atmosphere. Each overpressure history was approximated using the following formula:

$$\Delta p = a\, e^{-b\,t}$$

where *a* and *b* are constants. The parameter can be treated as a quasi-static pressure, *QSP*.

Figure 3 shows 2 exemplary experimental traces and their approximations. The overpressure signals were generated by the RDXph/Al–Mg charge detonated in the chamber filled with air. The main oscillations in the records are caused by shock wave reverberations at the chamber walls. Their amplitudes decrease with time.

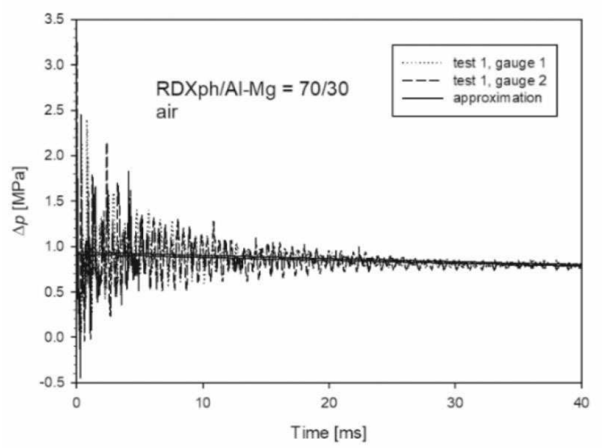


Figure 3. Overpressure records and their approximations for RDXph/Al–Mg.

The obtained *QSP* values are presented in Table 6.

Our previous paper [23] showed that the calculated equilibrium overpressure after detonation of 50 g RDXph charge in the chamber filled with argon was 0.78 MPa. The mass of RDXph in the charges tested in this work was 35 g (70% out of 50 g), so that, if the additives are chemically inert, then the overpressure in the chamber should not be higher than 0.55 MPa. The average *QSP* for the tested explosives ranged from 0.68 to 0.79 MPa (Table 6). This means that a significant part of the supplementary fuels reacted with RDX detonation products in anaerobic reactions.

Similar to the heat measured in the calorimetric bomb, the lowest values of *QSP* in the argon atmosphere were recorded for the mixture containing silicon, but the highest values were measured for RDXph/Al (0.79 MPa) and RDXph/Mg (0.74 MPa). However, there is no full correlation between *QSP* and the detonation heat results, because not RDXph/Al, but RDXph/Al–Mg composition has the highest detonation heat of 7640 J/g (Table 5).

QSP values in air are much higher than those measured in argon (Table 6). Thus, additives react with oxygen from air, and the amount of additional heat and the overpressure inside the chamber increase. Also, in this atmosphere, Al and Mg perform better than other additives (0.97 MPa and 0.96 MPa respectively). Surprisingly high *QSP* occurs with the explosive containing Si powder (0.95 MPa). In contrast to anaerobic reactions, this additive turns out to be nearly as reactive as aluminium and magnesium powders in an aerobic environment.

QSP for neat RDXph in air was determined to be 0.88 MPa. Assuming chemical internees of the tested additives, the overpressure for the explosives should be 0.62 MPa (70% out of 0.88 MPa). In reality, a considerable part of all the fuels burns in atmospheric oxygen, because the air *QSP* ranges from 0.92 to 0.97 MPa.

Table 6. Average *QSP* results for explosions in argon and air.

Explosive	Argon atmosphere		Air atmosphere	
	QSP [MPa]	Standard deviation	*QSP* [MPa]	Standard deviation
RDXph	–	–	0.88	0.05
+30% Al	0.79	0.04	0.97	0.02
+30% Al–Mg	0.72	0.01	0.92	0.01
+30% Mg	0.74	0.02	0.96	0.04
+30% Si	0.68	0.03	0.95	0.03

4 Conclusions

Compositions containing 30% of Al, Mg, or Al–Mg powders produce much more energy during detonation in the calorimetric bomb filled with argon than passivated RDX itself. The energy contribution of the metals reactions with RDX detonation products equals respectively 3700 J/g, 3560 J/g and 4150 J/g. So that detonation calorimetry results indicate that Al–Mg powder is a more effective additional fuel during anaerobic post-detonation reactions than Al and Mg powders separately. Silicon also exothermically reacts with RDXph detonation products in the calorimetric bomb, but the released heat (energy contribution 1640 J/g) only compensates for the lower amount of RDXph in the charge.

The *QSP* values determined using the overpressure histories from the explosion chamber filled with argon also indicate that the additives react with the detonation products in an anaerobic environment. Similar to the calorimetric measurements, the lowest value of *QSP* was obtained for the mixture with Si powder. The advantage of Al–Mg alloy over Al and Mg powders in energy efficiency, visible during calorimetric measurements, was not confirmed by *QSP* values. Both during the explosion in argon and in air atmosphere, Al and Mg turned out to be a slightly better additional fuels than their alloy.

The *QSPs* of air explosions are much higher than those obtained in an argon atmosphere. This implies that all the additives are able to react with oxygen from air under the experimental conditions. Surprisingly high *QSPs* in air explosions were measured for the Si-containing explosive. In contrast to anaerobic reactions, silicon turns out to be nearly as effective an additional fuel as aluminium and magnesium powders under aerobic conditions. It should be used in TBX compositions together with other easily combustible metals and/or oxidizers (preferably together with Al) to achieve more complete anaerobic combustion in the initial stages of expansion of the detonation products.

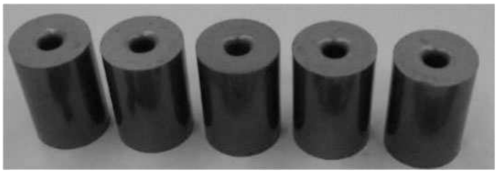
Acknowledgements

This work was carried out for DSTL under contract DSTL/AGR/00635/01. The authors would like to thank Anthony Kosecki from DSTL for the technical discussion.

References

[1] P. Vadhe, R. Pawar, R. Sinha, S. Asthana, A. Subhananda Rao, Cast Aluminized Explosives (Review), *Combust. Explos. Shock Waves* **2008**, *44*, 461–477.
[2] S. Kolev, T. Tzonev, Solid State Fuel-air Explosives with Enhanced Power and Stability, *46th Int. Annual Conference of ICT*, Karlsruhe, Germany, June 23–26, **2015**; S. Kolev, T. Tsonev, R. Weinheimer, Solid State Fuel-air Explosives, https://www.academia.edu/37894852.
[3] L. Turker, Thermobaric and Enhanced Blast Explosives (TBX and EBX), *Defence Technology* **2016**, *12*, 423–445.
[4] W. Trzciński, L. Maiz, Detonation Characteristics of New Aluminized Enhanced Blast Composites, *Propellants Explos. Pyrotech.* **2018**, *43*, 650–656.
[5] X. Xing, S. Zhao, Z. Wang, G. Ge, Discussions on Thermobaric Explosives (TBXs), *Propellants Explos. Pyrotech.* **2014**, *39*, 14–17.
[6] N. H. Yen, L. Y. Wang, Reactive Metals in Explosives, *Propellants Explos. Pyrotech.* **2012**, *37*, 143–155.
[7] A. Gany, D. W. Netzer Fuel Performance Evaluation for the Solid-Fueled Ramjet, *International Journal of Turbo and Jet Engines*, **1985**, *2*, 157–168, DOI: 10.1515/TJJ.1985.2.2.157.
[8] W. S. Holmes, Heat of Combustion of Phosphorus and The Enthalpies of Formation of P_4O_{10} and H_3PO_4, *Trans. Faraday Soc.* **1962**, *58*, 1916–1925, DOI: 10.1039/TF9625801916.
[9] R. A. Schaefer, S. M. Nicolich, Development and Evaluation of New High Blast Explosives, *Insensitive Munitions & Energetic Materials Technical Symposium, (IMEMTS 2004)*, San Francisco, CA, USA, November 15–17, **2004**.
[10] W. Cao, Q. Song, D. Gao, Y. Han, S. Xu, X. Lu, X. Guo, Detonation Characteristics of an Aluminized Explosive Added with Boron and Magnesium Hydride, *Propellants Explos. Pyrotech.* **2019**, 44, 1393–1399.
[11] E. C. Koch, D. Clement, Red Phosphorus-based Enhanced Blast Explosives, *38th Int. Annual Conference of ICT*, Karlsruhe, Germany, June 26–29, **2007**.
[12] A. Hahma, K. Palovuori, Y. Solomon, TNT-equivalency of Thermobaric Explosives, *36th Int. Annual Conference of ICT*, Karlsruhe, Germany, June 28 - July 1, **2005**.
[13] S. H. Fischer, M. C. Grubelich, The Use of Combustible Metals in Explosive Incendiary Devices, *Sandia National Laboratories, Defense Exchange Agreement 5642 Meeting*, Lawrence Livermore National Laboratory, Livermore, CA, USA, July 22–23, **1996**.
[14] R. W. Griffin, *Fire Starter and Method*, US Patent 3,927,993, **1975**.
[15] C. F. Lucy, *Metallic Sponge Incendiary Compositions*, US Patent 4,131,498, **1978**, Teledyne Industries, Inc, Albany OR, USA.
[16] P. E. Anderson, P. Cook, A. Davis, K. Mychajlonka, M. Mileham, Silicon Fuel in High Performance Explosives, *Propellants Explos. Pyrotech.* **2014**, *39*, 74–78.
[17] P. Dearden, New Blast Weapons, *J. R. Army Med. Corps*, **2001**, *147*, 80–86.
[18] A. Wildegger-Gaissmaier, Aspects of Thermobaric Weaponry, *ADF Health*, **2003**, *4*, 3–6.
[19] I. Glassman, *Combustion*, 3rd Edition, Academic Press, San Diego, CA, USA, **1996**.
[20] S. Cudziło, J. Paszula, R. Trębiński, W. A. Trzciński, P. Wolański, Studies of Afterburning of TNT Detonation Products in Confined Explosions, *Arch. Combust.*, **1997**, *17*, 129–144.
[21] W. A. Trzciński, K. Barcz, J. Paszula, S. Cudziło, Investigation of Blast Performance and Solid Residues for Layered Thermobaric Charges, *Propellants Explos. Pyrotech.* **2014**, *39*, 40–50.
[22] Q.-L. Yan, W. A. Trzciński, S. Cudziło, J. Paszula, T. Eugen, M. Liviu, R. Traian, M. Gozin, Thermobaric Effects Formed by Aluminium Foils Enveloping Cylindrical Charges, *Combust. Flame*, **2016**, *166*, 148–157.
[23] S. Cudziło, W. A. Trzciński, J. Paszula, M. Szala, Z. Chyłek, Effect of Titanium and Zirconium Hydrides on the Parameters of Confined Explosions of RDX-Based Explosives – a Comparison to Aluminium, *Propellants Explos. Pyrotech.* **2018**, *43*, 1048–1055.

Manuscript received: April 24, 2020
Revised manuscript received: June 26, 2020
Version of record online: ■■■, ■■■■



S. Cudziło*, W. A. Trzciński, J. Paszula, M. Szala, Z. Chyłek

1 – 8

Performance of Magnesium, Mg-Al Alloy and Silicon in Thermobaric Explosives – A Comparison to Aluminium