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Research paper

Application of 1,1-Diamino-2,2-dinitroethene (FOX-7, DADNE) in a Thermobaric Explosive Composition (TBX) with Reduced Sensitivity to Mechanical Stimuli

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Abstract: The present study aimed to verify the potential of 1,1-diamino-2,2-dinitroethene (FOX-7) in a Thermobaric Explosive Composition (TBX). Samples based on FOX-7, hexogen, octogen and pentrite phlegmatised with wax, and with the addition of aluminium-silicon (Al:Si) alloy powder were subjected to stimulus sensitivity tests, and the blast wave characteristics, quasi-static pressure at constant volume (QSP), the heat of explosion and detonation velocity were measured. A method for determining the heat of explosion (11.4 kJ) of the detonator used to initiate the blast by calorimetric heat measurement was proposed and positively verified. Compared to RDX or HMX, the FOX-7-based composition was twice as insensitive to excitation stimuli such as friction and impact (330 N and 10 J, respectively). Except for the PETN-based mixture, the remaining samples ignited when heated above 210 °C. In general, the explosive properties of the FOX-7 and Al:Si mixture were the weakest compared to the other explosives tested, but the parameters important to the thermobaric process, such as the overpressure wave impulse and QSP, were relatively high and satisfactory. The results of the thermochemical calculations correspond essentially to the experimental ones.

TBX compositions with FOX-7 may be a safer alternative in production and use compared to typical compositions of this type, such as those based on RDX.

Keywords: thermobaric explosive, TBX, FOX-7, low sensitivity, wax, aluminium-silicon alloy

1 Introduction

The development of modern thermobaric explosive compositions (TBXs) represents a flourishing branch of military technology [1, 2]. TBX materials have undergone various stages of development, ranging from the use of liquid fuels that are ignited after prior explosive dispersion in air, to the construction of solid explosive charges of complex design containing significant additions of solid fuels [3-5], as well as typical high explosives (*e.g.* HMX, RDX). Additives in the form of metal powders (*e.g.* aluminium, beryllium, titanium, zirconium, *etc.*) or non-metals (*e.g.* boron, silicon) [6-8], their alloys and mixtures, or chemical compounds (*e.g.* metal hydrides) [9, 10] have been proposed as solid fuels. In each case, the behaviour of the solid fuel additive, following explosive dispersion in the air, is analogous in that it results in the initiation of an explosive reaction of the fuel-air mixture. The impact of this reaction, in conjunction with the overpressure wave and thermal energy that is generated, is considerably prolonged in duration when compared to the impact of conventional explosive charges. The time-extended overpressure pulse is known to be highly destructive, even for living objects not directly exposed to a shock wave.

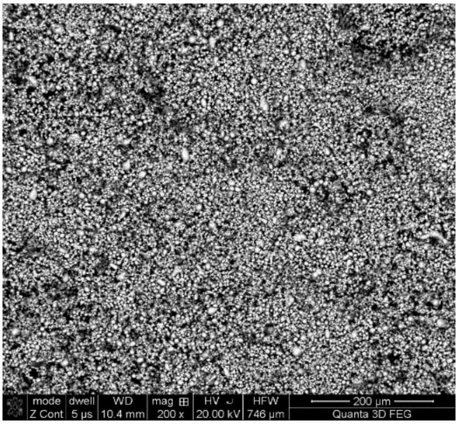
The present work presents the small-scale manufacture and investigation of the sensitivity and basic explosive parameters of compositions of selected explosives (PETN, RDX, HMX, FOX-7), which, after phlegmatisation, were mixed with fuel in the form of aluminium-silicon alloy powder. Industrial techniques, involving the pressurised spraying of molten metal mixtures in a cooling inert gas atmosphere, have been demonstrated to yield powders with favourable sizes (mainly below 45 μm) and spheroidal shape [11]. The spherical particles permit high packing densities, and their surface, devoid of sharp edges, does not significantly enhance the sensitivity to mechanical stimuli in a mixture with a crystalline explosive.

Hexogen (RDX), octogen (HMX) and pentaerythritol tetranitrate (PETN) are powerful explosives that are frequently employed in military technology. It is probable that 1,1-diamino-2,2-dinitroethene (FOX-7, DADNE) has not yet been incorporated into this group. This compound has been extensively studied over the course of approximately 25 years for a variety of applications [12-15]. In the field of explosives research, FOX-7 has frequently been advanced as a possible substitute for RDX. This proposal is based on the observation that FOX-7 exhibits a comparable explosive performance and a significantly reduced sensitivity to accidental ignition [16-19].

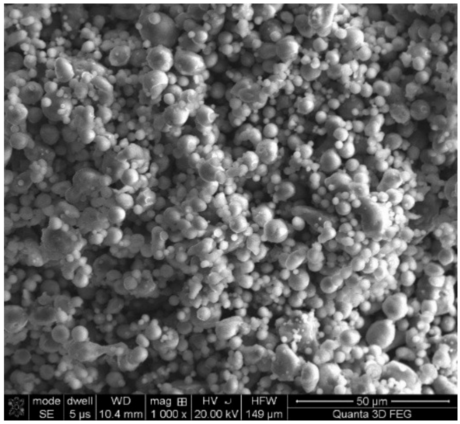
As part of the research that was conducted, a proposal was made to prepare and compare the properties of four mixtures composed of the phlegmatized explosive (70 wt.%) and 30 wt.% of aluminium/silicon alloy powder (Al:Si). The objective of the research was to ascertain whether FOX-7 can be regarded as a primary explosive in thermobaric compositions and whether such products can provide high explosive performance (including specific thermobaric effects) in comparison to mixtures based on RDX, HMX and PETN. A further criterion to be considered is the determination of whether FOX-7-based compositions have the potential to offer a heightened degree of safety, attributable to the anticipated diminished sensitivity to accidental ignition.

2 Materials

The explosives used in these experiments were FOX-7 (synthesised in our laboratory), RDX, HMX, PETN (supplied from NitroChem, Poland), and aluminium-silicon alloy powder ~325 mesh, with a 50/50 wt. (Al:Si) supplied from Stanford Advanced Materials, USA. The explosives were first coated with paraffin wax from Roth (6 wt.%). An investigation was conducted into the morphology and chemical composition of the powders. This was achieved by utilising a Quanta 3D FEG scanning microscope in conjunction with an EDS EDAX Octane Elect Plus X-ray energy dispersive spectrometer, which operated at an accelerating voltage of 20 kV and a beam current of 8 nA. Prior to the commencement of the testing procedure, the material under study was affixed to conductive graphite tape. The SEM and spectrometric analysis of the elements in the powder are presented in Figure 1. The elemental composition of the Al:Si alloy powder is shown in Table 1.



(a)



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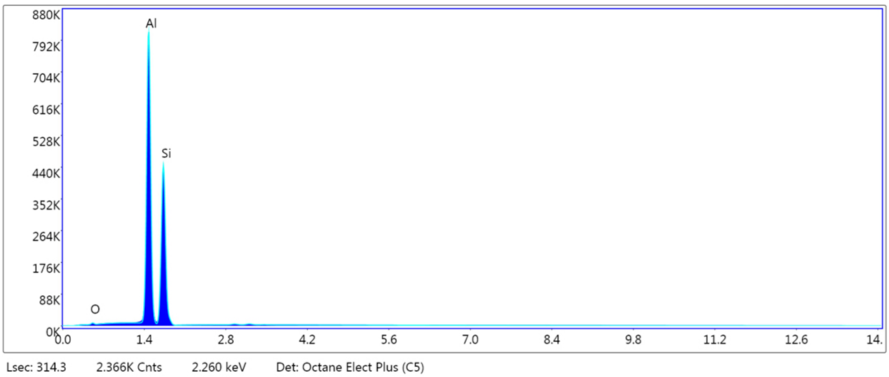

(c)

Figure 1. SEM microscopic examination of the Al:Si alloy powder used: SEM images (a, b), and results of the atomic composition analysis (c)

Table 1. Elemental composition of the Al:Si alloy powder

Element	Weight [%]	Atomic [%]
O K	1.54	2.63
Al K	48.61	49.05
Si K	49.84	48.32

The crystalline explosive materials were mixed with the wax solution in hexane until the majority of the solvent had evaporated, resulting in a granular product. The product was then subjected to a drying process at a temperature of 50 °C for the duration of 3 h. In the production of the TBX granulated samples, the phlegmatised explosives, namely FOX-7_{wax}, RDX_{wax}, HMX_{wax} or $PETN_{wax}$ (70 wt.%), respectively, and Al:Si powder (30 wt.%) were used. The components were then mixed meticulously following a process of wetting with ethanol. The resulting granule samples were then subjected to drying at a temperature of 50 °C for a period of 3 h. The resulting products were then utilised in the manufacture of pressed explosive charges for the subsequent experiments.

3 Test Methods

3.1 Sensitivity to mechanical stimuli measurement

The impact sensitivity of the prepared granular samples was assessed using a BAM apparatus with a 5 kg hammer. The minimum drop height at which initiation is observed at least once in six tests was determined. The measurement of friction sensitivity was conducted utilizing a Julius-Peters machine. The minimum loading of the pistil was determined at which initiation was observed at least once in six trials. Both methods were applied as described in [20].

3.2 Heat sensitivity measurement

The sensitivity of the samples to thermal stimuli was determined by measuring the decomposition temperature using a Stuart Scientific Melting Point Apparatus SMP3. Samples in glass capillaries were heated at a rate of 5 °C/min to temperatures ranging from 140 to 300 °C. The decomposition temperature was determined through the observation of the release of gaseous products from the test sample.

3.3 Heat of explosion measurement

The measurements were conducted using a calorimetric system incorporating a steel bomb with a volume of 5.6 dm^3. The explosive device is situated within a steel tank that contains 27,000 g of water, with a standard deviation of ±1 g. The tank containing the explosive device is encased in a constant-temperature jacket, which serves to regulate the ambient temperature of the surrounding environment. The temperature of the jacket was found to be 20.0 ±0.1 °C. The calorimetric constant of the device was measured by the heat of combustion of benzoic acid in an oxygen atmosphere at a pressure of 2.0 MPa. The calorimetric constant thus determined was 163.7 ±1.2 kJ/K.

3.4 Detonation velocity (VoD) measurements

The measurement of VoD was conducted through the utilisation of an electrical method, employing short-circuit sensors. This technique involves the measurement of the movement time of the detonation wave through sections of the tested charge, which are equipped with sensors. Initially, cylindrical molding of the test material, with a diameter of 25 mm and a height of approximately 25-30 mm, was conducted utilising the pressing method. Subsequently, sensors are positioned between the mouldings and the entire assembly is formed into a single large test charge. Upon initiation of the detonation process, the detonation wave activates the following sensors, thereby enabling the measurements of time and calculation of VoD for the multiple measuring points, thus facilitating the determination of the mean value.

3.5 Pressure history measurements in the chamber

The overpressure was measured in a chamber filled with air at atmospheric pressure in order to determine the quasistatic pressure after the explosion of 50 g charges of the tested explosives in a closed volume. The charges were positioned within a steel chamber, with a volume of 150 dm^3. The experimental design entailed the execution of at least two tests for each material. The overpressure was measured using two piezoelectric sensors (PCB Piezotronics, Inc., type 113B22, measuring range: 34475 kPa, resolution: 0.14 kPa, with a sensitivity of 0.145 mV/kPa), placed on the chamber wall. The signals from the sensors were recorded on a WAVEJET 314 oscilloscope. The sensors were mounted in special adapters with the objective of limiting the influence of gas-dynamic processes on the averaged overpressure history [8].

3.6 Blast waves characteristics measurements in the bunker

The experiments were performed in a bunker, and the layout is schematically depicted in Figure 2, illustrating the positioning of the charge and the gauges. The bunker had a volume of about 40 m^3 and had four small openings, each of which had a surface area of 0.05 m^2, in addition to a frontal opening with a surface area of about 1.3 m^2. The blast pressure history was measured by four pressure sensors from PCB Piezotronics, Inc. (type 137A22, measurement range: 3448 kPa, resolution: 0.069 kPa, sensitivity: 1.45 mV/kPa, rise time: <6.5 ms) fixed at distances of 2.0 m (two gauges) and 2.5 m (two gauges) from the charge. The tested charge and pressure sensors were placed 1.5 m above the ground in the bunker, and the sensors were directed toward the centre of the tested explosive. All gauges recorded the overpressure of the incident shock wave as it moved along the working surface of the devices. However, waves reflected from the bunker wall and the ground later reached these gauges from different directions, causing oscillations in the recorded waveforms.

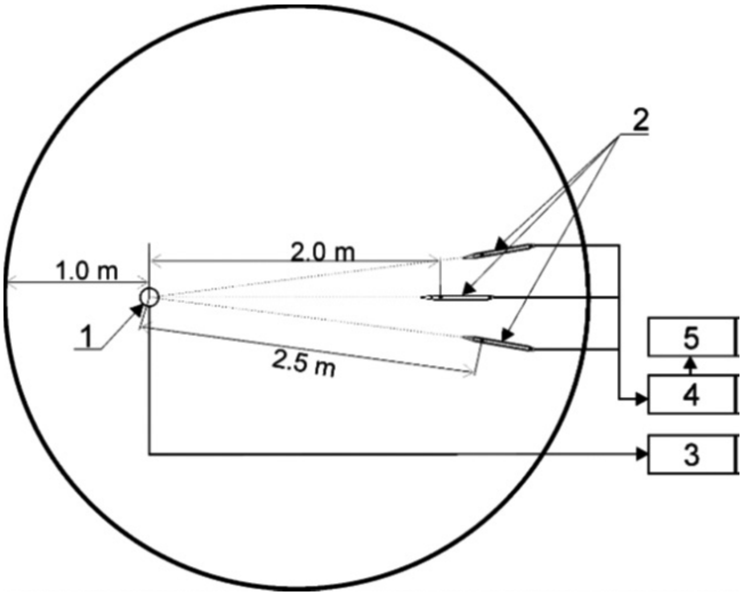

Figure 2. Diagram of the blast wave overpressure measurement system (top view): 1 – explosive charge, 2 pressure gauges, 3 – time meter, 4 – signal conditioner, 5 – oscilloscope

3.7 Calculation method

The program EXPLO5 v7.01.01 with the BKW standard parameter library (α = 0.5; β = 0.38; κ = 9.23; θ = 4250) was used for the thermodynamic calculations. Cases were analysed where the aluminium used was chemically active in the explosion phase at 100, 75, 40 and 0 (% act). The density values of the examined mixtures were used for the calculations.

4 Results

4.1 Sensitivity to mechanical and heat stimuli results

The results of the sensitivity testing of the mixtures are listed in Table 2. A simple comparative study of the mechanical stimuli sensitivity of the compositions obtained showed almost twice the impact resistance of the FOX-7/Al:Si mixture (10 J) compared to RDX/Al:Si (5.5 J). Mixtures containing HMX and PETN showed higher impact sensitivity than RDX/Al:Si. The comparison of friction sensitivity was analogous. The FOX-7/Al:Si mixture is almost friction insensitive (330 N), considering that, according to the test method, the lack of initiation for a value of 360 N in any of the six trials is treated as complete friction insensitivity. The other compositions were easier to initiate, with the PETN-containing mixture (126 N) being the most sensitive, as expected.

Table 2. Results of sensitivity measurements to mechanical stimuli and heat

Explosive material	Impact [J]	Friction [N]	Heat [°C]
RDX_{wax}	6.0	245	215.5
RDX_{wax}/Al:Si	5.0	218	212.5
FOX-7_{wax}	12.5	360	253.9
FOX-7_{wax}/Al:Si	10.0	330	250.0
$PETN_{wax}$	3.5	126	168.0*)
$PETN_{wax}$/Al:Si	3.5	126	165.8*)
HMX_{wax}	5.5	245	282.1
HMX_{wax}/Al:Si	4.5	218	279.5

*) at 147.9 and 149.7 °C the melting point of $PETN_{wax}$ and $PETN_{wax}$/Al:Si was observed, respectively

Sensitivity testing did not indicate any serious incompatibility between the explosives tested and the Al:Si alloy (Table 2). During heating of the PETN-containing sample, the nitroester first melted at 149.7 °C, which improved the contact between the mixture components, resulting in the initiation of decomposition, which was evident from the observation of bubbles of evolved gas (decomposition gas products) at 165.8 °C. Decomposition of the RDX/Al:Si and HMX/Al:Si mixtures occurred at 212.5 and 279.5 °C, respectively, corresponding to typical values characteristic of the transformation of the pure materials tested under the same conditions. The decomposition temperature for FOX-7/Al:Si was 250.0 °C, a typical value obtained under these conditions for the pure compound. Therefore, it can be assumed that the FOX-7/Al:Si mixture is thermally stable and, as expected, shows a higher thermal resistance than the RDX and PETN mixtures.

4.2 Heat of detonation results

4.2.1 The energy released by the detonator

To determine the contribution of the electric detonator to the measured thermal effect of the explosion of the tested materials, a series of measurements of the thermal effect of the explosion of TNT and RDX_{wax} charges of different masses was carried out. Assuming that the detonator's contribution to the calorimetric measurement does not depend on the mass of the charge used in the tests, the dependence of the measured heat on the mass of the charge should be linear.

Therefore, a series of measurements of the heat of detonation for charges of different masses will allow for the determination of the heat of detonation of the explosives used and the thermal contribution of the detonator. Three to five explosion heat measurement tests were performed for each mass of the tested explosive charges.

Figure 3 shows the results of measuring the thermal effect of the explosion of TNT and RDXwax charges of different masses along with the linear regression. It is possible to observe a linear dependence of the measured heat as a function of the charge mass. This observation means that the assumption of the independence of the detonator contribution from the detonated charge mass is valid.

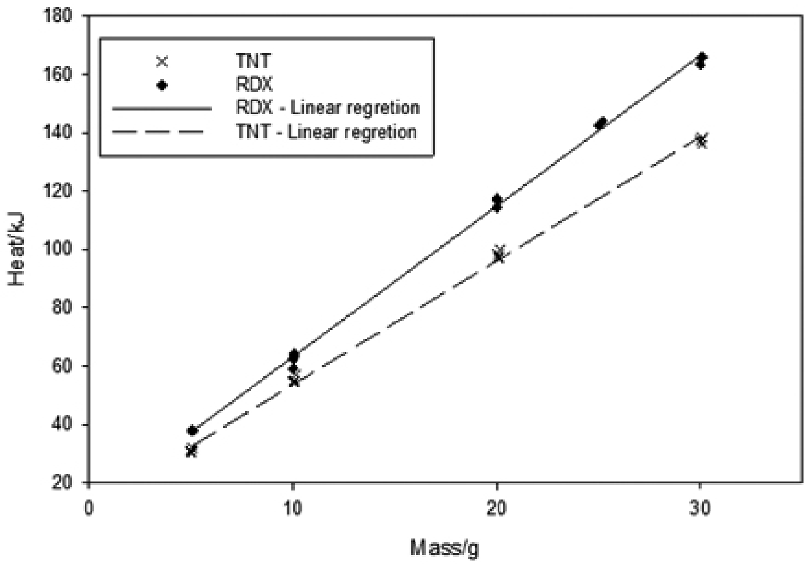

Figure 3. Heat of detonation measurement results for TNT and RDX with different charge masses

The results of linear regression for the tested series of charges can be written in the form:

$$Q_t = Q_v * m + Q_f \quad (1)$$

where Q_t is the total heat effect (in kJ), Q_v is the heat of explosion of the tested explosive material (in kJ/g), m is the mass of the explosive charge (in g) and Q_f is the contribution of the fuse to the total thermal effect (in kJ). The heat values determined in this way are listed in Table 3.

Table 3. Linear regression coefficients for the dependence of the thermal effect of the explosion on the charge masses for TNT and RDX_{wax}

Explosive material	Q_v [kJ·g^{-1}]	Q_f [kJ]
TNT	4.25 ±0.05	11.0 ±0.8
RDX_{wax}	5.17 ±0.05	11.4 ±0.8

As can be seen, the type of explosive used in the tests does not significantly affect the detonator's contribution to the measured calorimetric heat. The detonator's contribution was assumed to be 11.4 kJ in further tests.

4.2.2 Heat of explosion of the tested explosive mixtures

In these tests of the explosion heat, pressed charges of the selected mixtures weighing approximately 25 g were used. The charges were detonated in a calorimetric bomb filled with argon at a pressure of 2.0 MPa. To calculate the heat of detonation of the 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.

Table 4 presents the collected experimental results of the heat of detonation (Q_{exp}) measurements. Additionally, the results of the heat of detonation calculations and the TNT and RDX equivalents for the tested mixtures are presented for comparison. The experimental values of the heat of detonation of the tested explosive mixtures were compared to the heat of detonation of TNT and RDX_{wax}.

Table 4. Experimental (Q_{exp}) and calculated (Q_{calc}) heats of detonation and TNT and RDX equivalents

Explosive material	Density [g·cm^{-3}]	Q_{exp} [J·g^{-1}]	Q_{calc} [J·g^{-1}]	TNT equivalent	RDX_{wax} equivalent
TNT	1.620	4250 ±50	4460	1.00	0.78
RDX_{wax}	1.660	5450 ±10*)	5475	1.28	1.00
RDX_{wax}/Al:Si	1.771	6690 ±40	6645	1.57	1.23
FOX-7_{wax}	1.709	4290 ±20	4830	1.01	0.79
FOX-7_{wax}/Al:Si	1.832	3350 ±20	3875	0.79	0.61
$PETN_{wax}$	1.623	5520 ±40	5525	1.30	1.01
$PETN_{wax}$/Al:Si	1.756	7320 ±50	7350	1.72	1.34
HMX_{wax}	1.745	5750 ±50	5540	1.35	1.06
HMX_{wax}/Al:Si	1.820	6530 ±10	6610	1.54	1.20

*) Ref. [8]

4.3 Blast wave characteristics

Exemplary overpressure histories measured for the primary shock waves in the bunker at distances of 2.0 and 2.5 m after detonation of RDX_{wax}/Al:Si with a mass of 250 g are presented in Figure 4. The modified Friedlander equation was fitted to the primary wave's overpressure ([21]):

$$\Delta p(t) = P_s\, e^{-\alpha t}\left(1 - \frac{t}{\tau}\right) \quad (2)$$

where P_s is the amplitude of the incident wave, α and τ are constants. In this case, the constant τ denotes the duration of the positive phase.

For comparison purposes, TNT equivalents were calculated using the total impulse for 40 ms (α_{TIV}), specific impulse (α_{TI}) and primary shock peak overpressure (α_{TP}) values. These equivalents were determined using the methodology described in [22]. The equivalent values for 2.0 and 2.5 m were averaged. Finally, the total TNT equivalent () was calculated as the average value of the determined equivalents. All TNT equivalents for the tested charges are listed in Table 5.

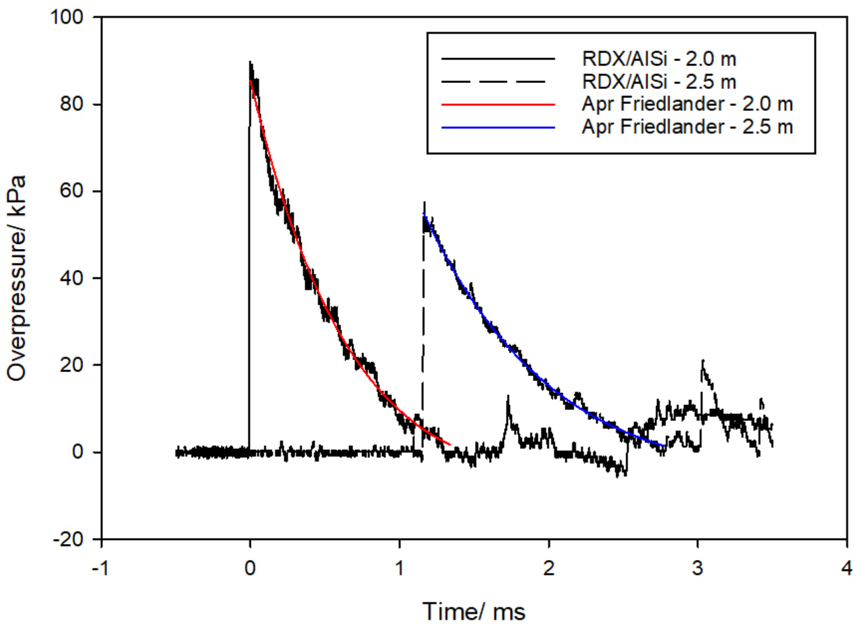

Figure 4. Approximation of the incident blast wave profiles for the RDX_{wax}/Al:Si explosive mixture (distance 2.0 and 2.5 m)

Table 5. Blast wave characteristics and their TNT equivalence

Explosive material	Overpressure [kPa]			Impulse [Pa·s]			Impulse40 [Pa·s]			α_T
	2.0 m	2.5 m	α_{TP}	2.0 m	2.5 m	α_{TI}	2.0 m	2.5 m	α_{TIV}	
TNT	76 ±2	49 ±1	1.04	33 ±1	29 ±1	1.00	740 ±80	710 ±30	1.05	1.03
RDX_{wax}/Al:Si	87 ±4	57 ±1	1.23	39 ±1	33 ±1	1.26	790 ±10	850 ±20	1.21	1.23
$PETN_{wax}$/Al:Si	80 ±5	54 ±3	1.15	40 ±1	35 ±1	1.34	790 ±20	870 ±30	1.23	1.24
FOX-7_{wax}/Al:Si	71 ±5	45 ±1	0.95	35 ±1	31 ±1	1.10	780 ±70	760 ±30	1.13	1.06
HMX_{wax}/Al:Si	83 ±5	43 ±2	1.16	39 ±2	36 ±2	1.34	800 ±20	880 ±30	1.24	1.25

As demonstrated, TNT equivalents attain their maximum values for mixtures containing potent explosives such as RDX, PETN and HMX. The lowest equivalent value was observed for a mixture containing FOX-7. Nevertheless, its value is comparable to the values measured for TNT. It can also be observed that the FOX/Al:Si mixture, despite lower primary blast wave overpressure values, achieves higher positive phase blast wave impulse parameters by approximately 10%. Furthermore, the total pulse values for a time of 40 ms are also higher than those obtained for the TNT charge.

4.4 Quasi-static pressure

Three measurements were performed for each composition of the tested mixtures. In each case, two overpressure histories were recorded. Figure 5 shows an example of the recorded overpressure history. Oscillations of the overpressure value that result from reflection of the shock waves from the chamber walls and the vibrations of the sensor mounting system are visible. In order to determine the quasi-static pressure (QSP), the recorded overpressure course over time was approximated by the function:

$$\Delta p = a(1 - e^{-bt}) + ce^{-dt} \tag{3}$$

where a, b, c and d are constants, and t is time. The first term in Equation 3 describes the initial increase in the average overpressure caused by pressure equalisation in the chamber and the sensor socket and the combustion processes of the explosion products in the oxygen from the air in the chamber. The second term describes the slow decrease in the average overpressure in the chamber caused primarily by the cooling of the post-explosion gases. The approximation function is also presented in Figure 5. The function (Equation 3) reaches its maximum value at time t_{max}:

$$t_{max} = ln\left(\frac{a\,b}{c\,d}\right)\frac{1}{b-d} \tag{4}$$

We can assumed that the quasi-static pressure QSP is equal to .

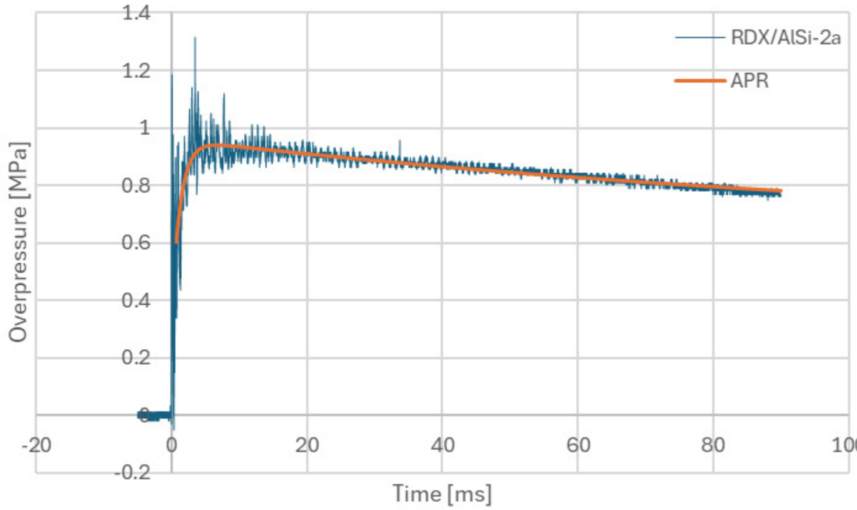

Figure 5. Example of overpressure history in the chamber after detonation of a 50 g RDX/AlSi charge and the approximation function

In [22], the QSP pressure was studied and its dependence on the loading density (load mass divided by the volume of the explosion chamber) was determined. The authors of [22] also presented a methodology for determining the TNT equivalent for an explosion in a closed volume (α_{TIV}).

The results of the experimental measurements of QSP pressure are listed in Table 6. Table 6 also includes the results of thermochemical calculations of the explosion pressure at a constant volume (P_{calc}) and the TNT equivalents determined for the tested explosive mixtures.

Table 6. Results of QSP pressure measurements and calculated values of TNT equivalents in a constant volume

Explosive material	QSP [MPa]	P_{calc} [MPa]	α_{TIV}
RDX_{wax}	0.85 ±0.02	1.02	0.90
RDX_{wax}/Al:Si	0.95 ±0.02	1.07	1.06
$PETN_{wax}$/Al:Si	0.87 ±0.02	1.01	0.94
HMX_{wax}/Al:Si	0.93 ±0.02	1.06	1.04
FOX-7_{wax}/Al:Si	0.86 ±0.02	1.03	0.93

As can be seen, the TNT equivalent of an explosion in a closed volume for the FOX-7_{wax}/Al:Si mixture is comparable to the results obtained for the other tested materials. However, the results of the thermochemical calculations of the overpressures in the chamber after explosion of the tested mixtures are significantly higher than the experimental values. This may be due to incomplete oxidation of the fuel in the explosive mixture.

4.5 VoD

Pressed charges with the density parameters specified in Table 4 were used to experimentally determine the VoD (Table 6). Depending on the explosive used in the tested compositions, the highest values, close to 7500 m/s, were obtained for RDX and HMX. PETN- and FOX-7-based mixtures reached values closer to 7000 m/s. Table 6 also shows the VoD calculation results (VoD_{calc}) for different degrees of aluminium reactivity in the explosion phase. The experimental results corresponded well with the calculated values, especially for the assumptions that the aluminium content that did not react directly in the explosion phase (inert Al) was high, in the 75-100% range. The exception is the FOX-7-based composition, where it is probable that the detonation process did not fully expand correctly, and therefore its VoD was lower than the calculated values. For the marked VoD_{calc} values, the parameter (inert Al) was included in calculating the heat of explosion values shown in Table 4.

Table 6. VoD measurements and calculation results (VoD_{C-J})

Explosive material	VoD [$m \cdot s^{-1}$]	Inert Al content [%]			
		0	40	75	100
RDX_{wax}/Al:Si	7420 ±80	7105	7250	7305*	7370
FOX-7_{wax}/Al:Si	6750 ±70	7195	7255	7355	7225*
$PETN_{wax}$/Al:Si	7130 ±70	6695	6935*)	7085	7115
HMX_{wax}/Al:Si	7540 ±80	7285	7370	7465*	7540

*) value corresponds to the calculated heat of detonation in Table 3

5 Conclusions

- Four TBX-type mixtures were prepared based on powerful strong explosives (RDX, HMX, PETN, FOX-7) and the addition of Al:Si alloy powder. In all cases, the proportion of the components was the same, 65.8, 4.2, and 30 wt.%, for the explosive, phlegmatizer (wax), and Al:Si, respectively.
- A study of the explosive/Al:Si compositions' heat-sensitivity confirmed good compatibility between the components. In no case did heating cause an undesirable chemical interaction below the characteristic decomposition temperature of the least thermally stable component (*i.e.* the explosive). Compositions with HMX and FOX-7 proved to be the most stable, decomposing at about 280 and 250 °C, respectively. Compositions containing RDX and PETN decomposed at 212 and 165 °C, respectively.
- Tests of sensitivity to mechanical stimuli (friction/impact) confirmed the high resistance to initiation (impact: 10 J, friction: 330 N) of the FOX-7/Al:Si composition compared to the rest of the mixtures. Compared to compositions with RDX and HMX (respectively – impact: 5.5, 4.5 J, friction: 218, 218 N), the results for the sample with FOX-7 were almost twice as high. The PETN-based composition was the least durable (impact: 3.5 J, friction: 126 N).
- In order to refine the measurement of the heat of explosion test, the amount of thermal energy (11.4 kJ) released by the type of igniter used in the tests was determined by linear regression. The determined heat of explosion of the FOX-7/Al:Si composition (3350 J/g) was about half that of the values obtained for RDX/Al:Si and HMX/Al:Si. In all cases, except FOX-7 compositions, the addition of solid fuel enhanced the heat of explosion obtained compared to the values obtained for the stand-alone explosives after wax phlegmatization.
- In the blast wave characteristics tests, the FOX-7/Al:Si composition, despite exhibiting the lowest maximum overpressure value, achieved an impulse comparable to other compositions and higher than pure TNT. The prolonged effect of the overpressure (impulse) is favourable due to the nature of TBX-type materials.
- The QSP values designated for the explosion overpressure in a closed volume for mixtures containing FOX-7 were comparable to those obtained for PETN-based mixtures and higher than those obtained for phlegmatised RDX-based mixtures.
- The VoD of FOX-7/Al:Si (6750 m/s) is the lowest of all the tested compositions, which may be related to using small-diameter charges. It is

expected that performing tests for explosive charges with larger diameters will allow for better verification, given that the detonation process will be more stable. Experimental results of the heat of explosion (at constant volume) and VoD correspond with theoretical values determined with the help of Explo5 software with acceptable accuracy. The calculations also indicate that the addition of solid fuel reacts to a small extent in the anaerobic phase of the explosive process. Such an effect is favourable due to the way TBX materials interact.

♦ These results confirmed the good properties of FOX-7 as an explosive with high potential for use in TBX-type compositions with enhanced stimulus insensitivity.

Acknowledgments

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References

[1] Xiao, L.X.; Sheng, X.Z.; Zhen, Y.W.; Guang, T.G. Discussions on Thermobaric Explosives (TBXs). *Propellants Explos. Pyrotech.* **2014**, *39*(1): 14-17; https://doi.org/10.1002/prep.201300003.

[2] Trzciński, W.A.; Maiz, L. Thermobaric and Enhanced Blast Explosives – Properties and Testing Methods. *Propellants Explos. Pyrotech.* **2015**, *40*(5): 632-644; https://doi.org/10.1002/prep.201400281.

[3] Türker, L. Thermobaric and Enhanced Blast Explosives (TBX and EBX). *Def. Technol.* **2016**, *12*(6): 423-445; https://doi.org/10.1016/j.dt.2016.09.002.

[4] Needham, C.E. *Blast Waves, Shock Wave and High Pressure Phenomena.* Springer, **2010**; ISBN 978-3-642-05287-3.

[5] Simić, D.; Andjelić, U.; Knežević, D.; Savić, K.; Draganić, V.; Sirovatka, R.; Tomić, L. Thermobaric Effects of Cast Composite Explosives of Different Charge Masses and Dimensions. *Cent. Eur. J. Energ. Mater.* **2016**, *13*(1): 161-182; https://doi.org/10.22211/cejem/64970.

[6] Ng, H.Y.; Lee, Y.W. Reactive Metals in Explosives. *Propellants Explos. Pyrotech.* **2012**, *37*(2): 143-155; https://doi.org/10.1002/prep.200900050.

[7] Cudziło, S.; Trzciński, W.A.; Paszula, J.; Szala, M.; Chyłek, Z. Performance of Magnesium, Mg-Al Alloy and Silicon in Thermobaric Explosives – A Comparison to Aluminium. *Propellants Explos. Pyrotech.* **2020**, *45*(11): 1691-1697; https://doi.org/10.1002/prep.202000103.

[8] Klapötke, T.M.; Cudziło, S.; Trzciński, W.A.; Paszula, J. Energy and Blast

Performance of Beryllium in a Model Thermobaric Composition in Comparison with Aluminium and Magnesium. *Def. Technol.* **2024**, *36*: 13-19; https://doi.org/10.1016/j.dt.2024.02.011.
[9] Cudziło, S.; Trzciński, W.A.; Paszula, J.; Szala, M.; Chyłek, Z. Effect of Titanium and Zirconium Hydrides on the Detonation Heat of RDX-based Explosives – A Comparison to Aluminium. *Propellants Explos. Pyrotech.* **2018**, *43*(3): 280-285; https://doi.org/10.1002/prep.201700237.
[10] Cudziło, S.; Trzciński, W.A.; Paszula, J.; Szala, M.; Chyłek, Z. 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*(10): 1048-1055; https://doi.org/10.1002/prep.201800054.
[11] Mi, G.; Li, C.; Wang, K.; Chen, L. Microstructure and Properties of 50Si50Al Alloy Fabricated by HPS Process using Overspray Powders. *Mater. Res. Innovations* **2013**, *17*: 182-185; https://doi.org/10.1179/1432891713Z.000000000212.
[12] Trzciński, W.A.; Belaada, A. 1,1-Diamino-2,2-dinitroethene (DADNE, FOX-7) – Properties and Formulations (a Review). *Cent. Eur. J. Energ. Mater.* **2016**, *13*(2): 527-544; https://doi.org/10.22211/cejem/65000.
[13] Chyłek, Z.; Jurkiewicz, R. Investigation of the Properties of Polymer Bonded Explosives Based on 1,1-Diamino-2,2-dinitroethene (FOX-7) and 1,3,5,7-Tetranitro-1,3,5,7-tetraazacyclooctane (HMX). *Cent. Eur. J. Energ. Mater.* **2016**, *13*(4): 859-870; https://doi.org/10.22211/cejem/67226.
[14] Jensen, T.L.; Unneberg, E.; Kristensen, T.E. Smokeless GAP-RDX Composite Rocket Propellants Containing Diaminodinitroethylene (FOX-7). *Propellants Explos. Pyrotech.* **2017**, *42*(4): 381-385; https://doi.org/10.1002/prep.201600278.
[15] Mishra, V.S.; Vadali, S.R.; Garg, R.K.; Joshi, V.S.; Wasnik, R.D.; Asthana, S. Studies on FOX-7 Based Melt Cast High Explosive Formulations. *Cent. Eur. J. Energ. Mater.* **2013**, *10*(4): 569-580.
[16] Belaada, A.; Trzciński, W.A.; Chyłek, Z.; Paszula, J. A Low-Sensitivity Composition Based on FOX-7. *Propellants Explos. Pyrotech.* **2017**, *42*(12): 1439-1445; https://doi.org/10.1002/prep.201700149.
[17] Belaada, A.; Trzciński, W.A.; Chyłek, Z.; Szala, M.; Paszula, J. A Melt-Cast Composition Based on NTO and FOX-7. *Cent. Eur. J. Energ. Mater.* **2016**, *13*(4): 882-902; https://doi.org/10.22211/cejem/65824.
[18] Li, X.; Yang, Y.; Song, C.; Sun, Y.; Han, Y.; Zhao, Y.; Wang, J. Fabrication and Characterization of Viton@FOX-7@Al Spherical Composite with Improved Thermal Decomposition Property and Safety Performance. *Materials* **2021**, *14*(5) paper 1093; https://doi.org/10.3390/ma14051093.
[19] Xiao, W.; Wu, X.X.; Huang, K.S.; Li, J.; Bi, L.X.; Wan, L.L.; Wang, B.L. Effect of FOX-7 on Explosion Performances and Afterburning of HMX-Based Thermobaric Explosives. *J. Phys.: Conf. Ser.* **2023**, paper 2478; https://doi.org/10.1088/1742-6596/2478/3/032035.
[20] Suceska, M. *Test Method for Explosives.* Springer-Verlag, New York, Inc, **1995**, pp. 21-28; ISBN 978-0-387-94555-2.

[21] Trzciński, W.A.; Paszula, J. Confined Explosions of High Explosives. *J. Techn. Phys.* **2000**, *41*(4): 453-470.
[22] Trzciński, W.A.; Paszula, J. Methods for Determining TNT Equivalents for Partially and Fully Enclosed Explosions. *Proc. 33rd Int. Symp. Ballistics*, Bruges, Belgium, **2023**, pp. 321-331.

Authorship contribution statement

Zbigniew Chyłek:	conception, foundations, methods, performing the experimental part, performing the statistical analysis
Józef Michał Paszula:	foundations, methods, performing the experimental part, performing the statistical analysis
Paweł Jóźwik:	methods, performing the experimental part, other contribution to the publication

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