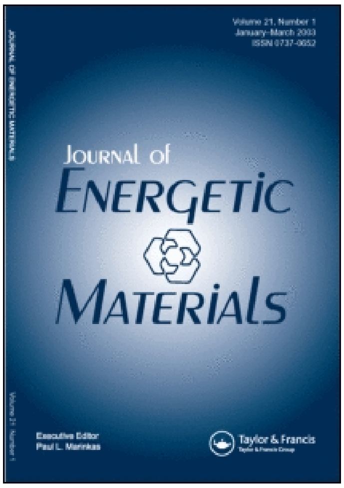

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Detonation Properties of Low-Sensitivity NTO-Based Explosives

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Detonating performance of new explosive compositions containing NTO, TNT, RDX, and HMX is investigated in this work. Detonation velocity, pressure, and energy of the mixtures tested as well as acceleration ability and the equation of state of their detonation products were determined. Shock and impact sensitivities were evaluated in the gap test and heavy hammer test. Reaction of the mixtures on jet penetration was also tested.

Keywords: NTO, detonation

Introduction

NTO (3-nitro-1,2,4-triazol-5-on) is commonly accepted as an ingredient of explosive compositions because of its relatively high performance and low sensitivity to mechanical stimuli [1]. A wide review of compositions containing NTO is made in [2]. From the review it follows that the low-sensitivity mixtures have been manufactured and tested. These compositions consisted of NTO and energetic binder [3], TNT [3–6], RDX [7], TNT and RDX [5–6], or HMX [4,8–13]. However, their detonation performance was usually lower than or comparable with those of

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composition B (TNT/RDX 40/60). That is why the problem of manufacturing insensitive NTO-based compositions with detonation parameters higher than those of composition B is still open.

This work attempts to obtain a low-sensitivity mixture of NTO, TNT, and RDX or NTO with HMX with high detonation and energetic performances. To select the composition contents the results of thermochemical calculations of detonation parameters are used. For chosen mixtures the detonation and energetic characteristics are determined. Shock, impact, and jet sensitivities of the compositions are also evaluated.

Compositions

Theoretical estimation of detonation characteristics of NTO-based mixtures was performed via the use of the thermochemical code CHEETAH [14]. The detonation velocity was calculated as a function of the mass contents of NTO in the HMX/NTO mixtures and in the TNT/RDX/NTO mixtures for a chosen amount of TNT. It was assumed that the density of the mixtures was 95% of their theoretical maximal density. The dependence of the detonation velocity D on the contents of NTO x_{NTO} is shown in Figures 1 and 2.

The detonation parameters of the TNT/RDX 40/60 mixture (hereafter denoted by CB) are assumed to correspond to the parameters of composition B. Detonation velocity of CB is indicated by a closed triangle symbol in Figure 1. From curves presented in Figure 1 it follows that the contents of TNT in a mixture TNT/RDX/NTO should be reduced to obtain a detonation velocity comparable with that of CB. The composition TNT/RDX/NTO 30/20/50 (denoted by C50) should have parameters similar to composition B. This mixture and the composition TNT/RDX/NTO 30/40/30 (denoted by C30) were chosen for investigations.

From the curve presented in Figure 2 it follows that for analyzed contents of NTO in the NTO/HMX mixtures, calculated detonation velocity is higher than that of CB. Similar to TNT/RDX/NTO mixtures, the compositions containing 30% or 50% of NTO were chosen for further investigations.

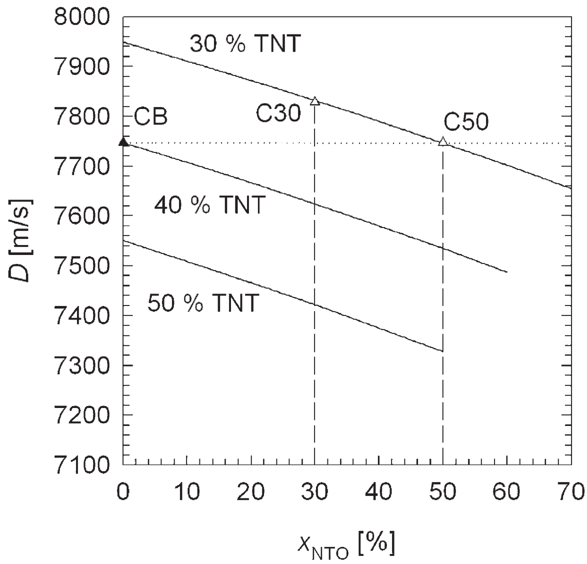

Figure 1. Dependence of detonation velocity of TNT/RDX/NTO mixtures on contents of NTO for different amounts of TNT.

Synthesis of NTO used in the mixtures was carried out by the method described in [15]. The procedure of preparing the compositions was as follows. NTO and RDX were added to melted TNT, and they were mixed. In this way the mixtures C30 and C50 were obtained. For the second type of mixtures, NTO was dissolved in water and HMX phlegmatized by Viton was added to the solution. The mixtures were frozen with continuous mixing, and finally the granulated product was obtained. The mixtures NTO/HMX/Viton 30/66.5/3.5 (denoted by CH30) and NTO/HMX/Viton 50/47.5/2.5 (denoted by CH50) were manufactured.

Detonation Performance

Detonation Pressure and Velocity

To determine the detonation pressure of the mixtures, a variant of the aquarium test was applied [16]. In this method, profiles of

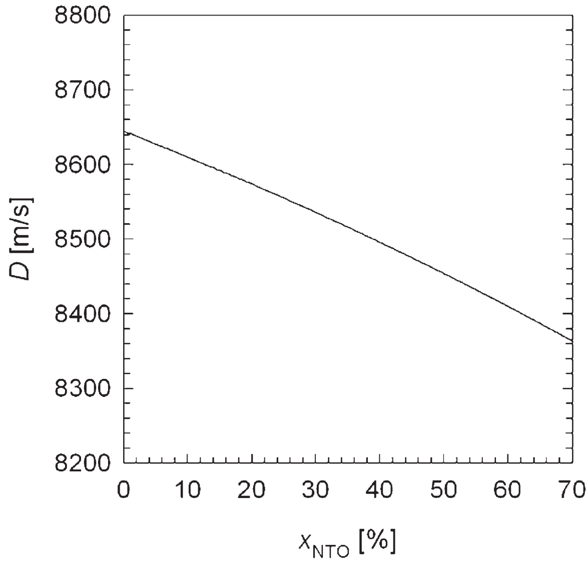

Figure 2. Dependence of detonation velocity of NTO/HMX mixtures on contents of NTO.

an oblique shock wave propagating in a cylindrical layer of water during detonation of a cylindrical charge of a tested explosive is recorded with an X-ray set. The experimental profiles are then compared with results of numerical modeling of the expansion process, which are in a form of relation between the position of the front of the oblique shock wave in water and the exponent of isentrope (γ) of detonation products. The value of γ corresponding to the solution that overlaps the experimental profile is accepted as the sought exponent. The detonation pressure is calculated according to the following equation:

$$p_{\rm CJ} = \frac{\rho_0 D^2}{\gamma + 1}, \tag{1}$$

where $p_{\rm CJ}$ denotes the detonation pressure and ρ_0 is a density of the explosive tested.

The scheme of the experimental arrangement, used in the aquarium test, is shown in Figure 3. A cylindrical charge of

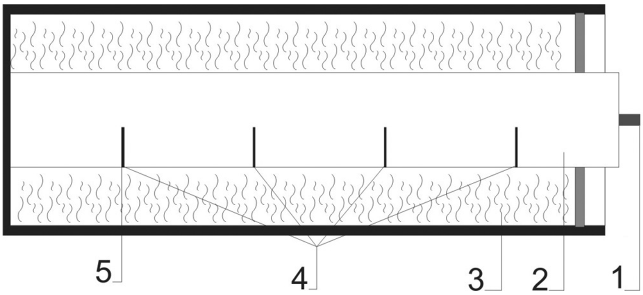

Figure 3. Aquarium test, experimental arrangement: 1—booster, 2—charge tested, 3—water, 4—sensor to measure detonation velocity, 5—sensor to trigger X-ray set.

25 mm in diameter and 250 mm in length was placed inside a PVC tube with an inner diameter of 71 mm and wall thickness of 2 mm. The tube was filled with water. Short-circuit sensors were located in the charge to measure detonation velocity. An exemplary X-ray photograph of the initial stage of the process of acceleration of a water envelope is presented in Figure 4.

The density and detonation velocity of the mixtures and the results of the aquarium test are given in Table 1. The exponent of isentrope of detonation products was determined by

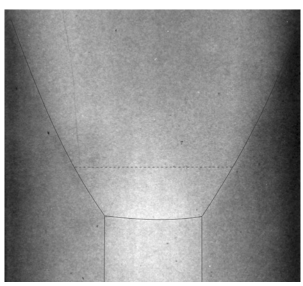

Figure 4. X-ray photograph of initial stage of acceleration of cylindrical layer of water by detonation products of CH50 with marked charge edges, detonation and shock waves (solid lines), and section at which radial positions of oblique shock wave were measured (dashed line).

Table 1
Experimental and calculated detonation properties of mixtures tested

Explosive	ρ_0 (kg/m^3)	D (m/s)	γ	p_{CJ}	D_t	γ_t	$p_{CJ,t}$
CB	1674	**7830**	**2.97**	**25.9**	7810	3.02	25.40
C30	1717	**7850**	**3.21**	**25.1**	7885	3.14	25.78
C50	1738	**7730**	**3.22**	**24.6**	7797	3.22	25.05
CH30	1810	**8580**	**3.20**	**31.7**	8517	3.26	30.82
CH50	1825	**8450**	**3.24**	**30.9**	8475	3.32	30.32

comparison of measured and calculated positions of the shock wave front in a plane section located at a distance of one charge radius from the front of the detonation wave (see Figure 4). The detonation pressure was calculated from Equation (1). Table 1 also contains some theoretical values of the parameters (with an index t) calculated with the thermochemical code CHEETAH.

From the results obtained it follows that the detonation parameters of composition C30 are close to those of composition CB. The detonation velocity and pressure of composition C50 are about 1% and 5% lower than those of CB, respectively. The detonation parameters of compositions CH30 and CH50 are significantly higher compared with those of CB.

Cylinder Test

The cylinder test results were the basis for determination of acceleration abilities and energetic characteristics of the detonation products of the mixtures investigated. The process of acceleration of a copper tube by detonation products was recorded with the impulse X-ray apparatus. The tube was 300 mm long with internal diameter of 25 mm and wall thickness of 2.5 mm.

A typical radiograph of the copper tube under the effect of the detonation products is shown in Figure 5. From the

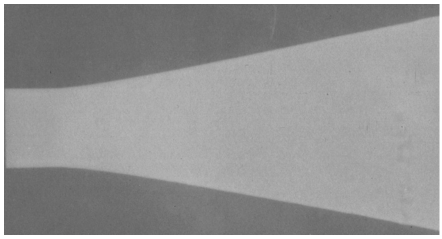

Figure 5. Radiograph of copper tube driven by detonation products of CH50.

photograph, the dependence of the external surface radius of the tube on an axial coordinate was determined using graphical computer programs. To determine the radial velocity of the copper tube, the data obtained from the cylinder test were recalculated using the method described in [17].

Gurney and Detonation Energy

The acceleration ability of an explosive can be described by the so-called Gurney energy. For cylindrical envelopes the Gurney energy is expressed by

$$E_G = \left(\mu + \frac{1}{2}\right)\frac{u_L^2}{2}, \tag{2}$$

where u_L is the velocity of the tube and μ denotes the ratio of tube mass to explosive mass.

Results of the cylinder test let us analyze the dependence of the Gurney energy, described by formula (2), on the degree of tube expansion. This dependence also describes the acceleration ability of the explosive. The relationship between the Gurney energy and the relative volume of detonation products for the mixtures tested is given in Figure 6.

The results of cylinder test also can be used to estimate the detonation energy. In [17] it is shown that a correlation exists between the velocity of driven tube at the infinite volume of the detonation products and the detonation energy of an

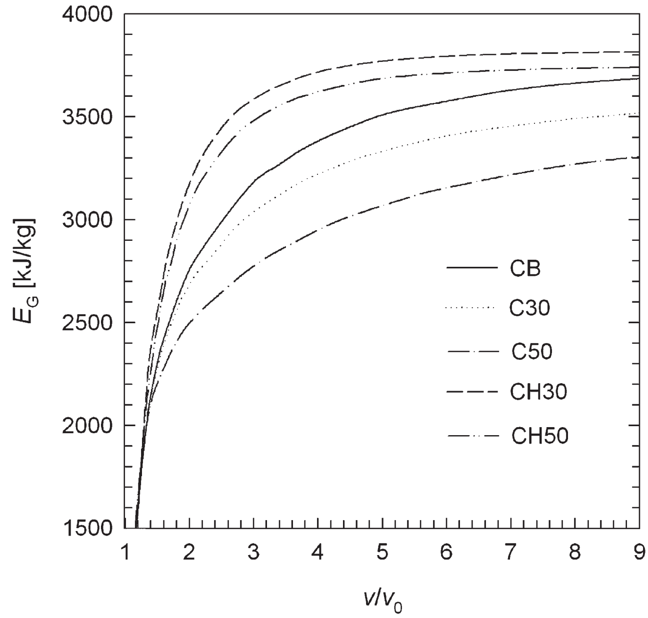

Figure 6. Acceleration ability of explosive tested.

explosive. The relation can be written as

$$\frac{e_0}{e_0^s} = \frac{\left(\mu + \frac{1}{2}\right)}{\left(\mu^s + \frac{1}{2}\right)} \left(\frac{u_L}{u_L^s}\right)^2, \tag{3}$$

where e_0 and e_0^s are the detonation energy of a given explosive and a standard explosive, respectively, and u_L and u_L^s denote the tube velocities determined by their extrapolation to the infinite volume of detonation products. These velocities were estimated by the method described in [17]. Using phlegmatized RDX as a standard explosive, the detonation energies of the explosive tested was calculated from Equation (3). The values obtained are given in Table 2.

From Table 2 it follows that the detonation energy per unit volume of compositions with RDX and TNT is a bit lower than that of CB mixture. That parameter for explosives with HMX is higher than that of CB mixture.

Table 2
Detonation energies estimated of basis of cylinder test data

Explosive	e_0 (kJ/kg)	$E_0 = e_0\rho_0$ (MPa)
RDX_{ph}	5263	8.7
CB	5126	8.6
C30	4911	8.4
C50	4700	8.2
CH30	5125	9.3
CH50	5000	9.1

Isentropes of the Detonation Products

The so-called effective exponent of isentrope of detonation products can be determined from results of the cylinder test. In [18] the effective exponent is determined via comparison of the experimental profile of the copper tube with that obtained from numerical modeling of the expansion process. The detonation products, driving the tube, are described by the constant-γ equation of state. This method was applied in the present work to estimate the effective exponent of isentrope for detonation products of explosive tested. The values of γ_{ef} are as follows: $\gamma_{ef} = 3.01$ and 3.10 for CB and C30, respectively, and $\gamma_{ef} = 3.15$ for compositions C50, CH30, and CH50.

In reality, the exponent of isentrope changes greatly during the expansion of the detonation products—from a value of about 3 at the Chapman-Jouguet point to approximately 1.2 at low pressure. Therefore the physical properties of the expanding gaseous detonation products are more precisely described by the isentrope that was proposed by Jones, Wilkins, and Lee [19]. Cylinder test results are commonly employed in most methods of determination of the JWL constants. In one of them [20], some connections between JWL coefficients are used. Using the model described in [21], as well as the values of detonation velocity, detonation pressure, and detonation energy of the explosive tested, the constants of the

Table 3
Detonation pressure and constants of JWL isentrope for detonation products of explosives tested

Explosive	p_{CJ} (GPa)	A (GPa)	B (GPa)	C (GPa)	R_1	R_2	ω
CB	25.85	705.261	11.9033	1.31774	4.80	1.31	0.33
C30	25.3	986.158	13.5494	1.16431	5.21	1.30	0.32
C50	24.7	951.452	12.6088	1.13379	5.16	1.33	0.30
CH30	31.9	1322.215	25.15556	0.933113	5.36	1.46	0.31
CH50	31.0	1386.098	25.34411	0.897686	5.46	1.46	0.31

JWL isentrope were estimated. Results of calculations are given in Table 3.

Expansion Work

After determining an isentrope, the expansion work of detonation products can be calculated from the equation

$$W(v) = -e_c + \int_{v_{CJ}}^{v} p_i dv, \tag{4}$$

where p_i is the pressure on the isentrope starting from the CJ point, and $e_c = (p_{CJ}–p_0)\ (v_0–v_{CJ})/2$ is the energy of compression of the explosive at the detonation front. Dependence of the expansion work on the relative volume of the detonation products of the explosives tested is shown in Figure 7.

C30 and C50 expansion work is lower than that of composition CB by about 3% and 6%, respectively. It is a surprising outcome, especially if we take into account the fact that the detonation parameters of these explosives are comparable (Table 1). However, capability to perform work and metal acceleration ability also depend on values of the isentrope exponent (γ or γ_{ef}). The effective exponent of isentrope of composition CB ($\gamma_{ef} = 3.01$) is significantly lower than that of C30

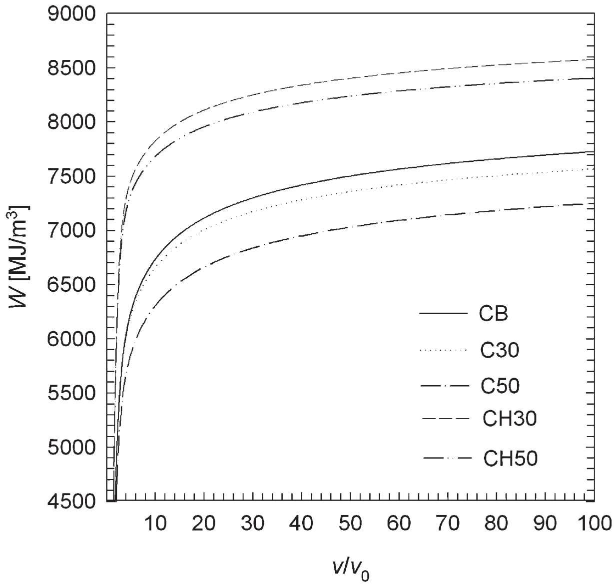

Figure 7. Expansion work as function of relative volume of detonation products.

$\gamma_{ef} = 3.10$) and C50 ($\gamma_{ef} = 3.15$). High value of the exponent means that parallel to an increase in the volume of detonation products their pressure decreases with a higher rate and their influence on surroundings is less effective.

Sensitivity to Mechanical Stimuli

Hammer Test

For the impact sensitivity determination a fallhammer apparatus was used. A 0.03 g sample of the explosive tested was placed in a piston device. The weight of hammer applied was 5 kg. For each drop height 10 trials were conducted. The maximum drop height H_0 was determined at which 10 lack-of-initiation trials were observed. The results are presented in Table 4. NTO admixture decreases significantly the sensitivity of tested mixtures.

Table 4
Impact sensitivity results

	Explosive				
Drop height	CB	C30	C50	CH30	CH50
H_0 (cm)	8	24	29	19	21

Gap Test

The gap test enables the determination of the shock sensitivity of explosives. The charge configuration used in our experiments is shown in Figure 8. The explosive tested was placed inside a copper tube similar to that used in the cylinder test. A booster made of phlegmatized RDX served as a shock wave generator. From shot to shot, the length of the plexiglass attenuator was changed with 1 mm steps. The highest and lowest gap values were appointed for which the complete detonation and failure of explosion process were observed. The complete detonation

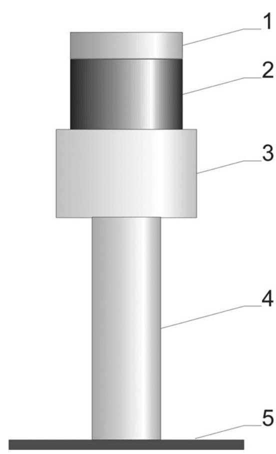

Figure 8. Scheme of charge configuration to determine shock sensitivity: 1—detonator and holder, 2—booster, 3—plexiglass gap, 4—explosive tested in copper tube, 5—witness plate.

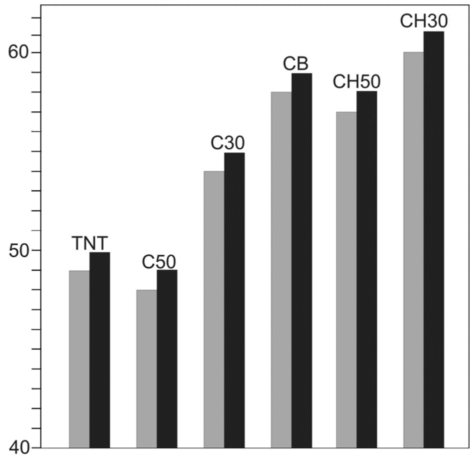

Figure 9. Thickness of plexiglass gap for complete and incomplete detonation in explosives tested.

of the explosive charge was indicated by a clean hole cut in the steel witness plate.

The shock sensitivity of the explosive tested as the usual gap results in the form ‘‘detonation–no detonation’’ is presented in Figure 9. The sensitivity of TNT/RDX mixtures with NTO is lower than that of composition CB. Compositions with HMX are slightly more or less sensitive than CB. For comparison, the results obtained for TNT are also shown.

The mean shock wave velocity of the explosion process propagation in the acceptor charge was measured by short-circuit sensors. The results obtained for composition C50 are shown in Figure 10.

Shaped Charge Jet Initiation

The reaction of new explosive mixtures to a jet attack was studied experimentally in the system shown in Figure 11. Two rectangular steel plates were separated by a layer of the explosive tested. The shaped charge was placed above the upper steel plate. The distance of 80 mm between the charge and the plate was established by a vinyl tube. Two types of

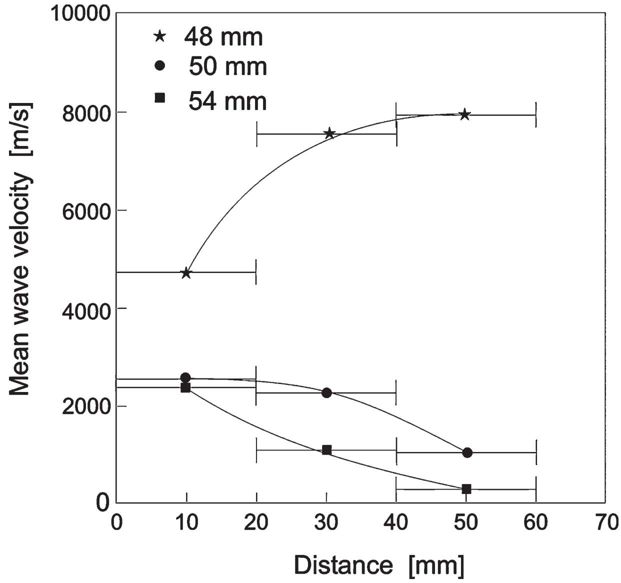

Figure 10. Mean velocity of wave in charge C50 at consecutive measuring distances as function of distance from end of plexiglass gap for different lengths of gap.

shaped charge were applied. The first charge had 37 mm diameter and 32 g mass and was used with sintered copper liners of about 35 g mass, 1.37 mm thickness, and cone shape with 42° angle (charge C-1). The second one of 34 mm diameter and 20 g mass was used with sintered copper liners of spherical shape (charge C-2). The X-ray impulse photography was applied to record the motion of plates.

Before the main tests the characteristics of cumulative jets were determined. The photographs of the shape of jet were taken at a different delay from the moment when the detonation had been initiated in the shaped charge. Estimated velocities of the jet head were 8260 and 3240 m/s for charges with conical (C-1) and spherical (C-2) liners, respectively. The Held u^2d-parameter, defined in [22], is 40 mm^3/μs^2 for C-1 and or 17 mm^3/μs^2 for C-2 charge.

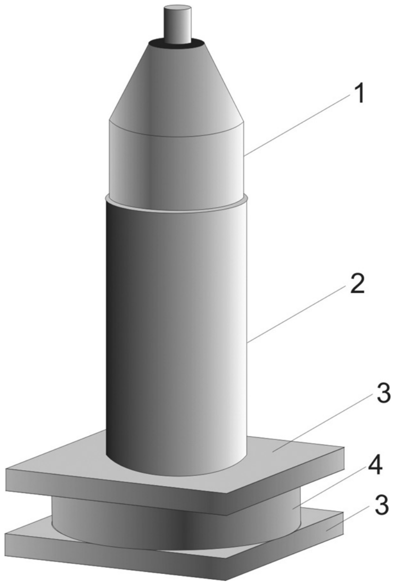

Figure 11. Diagram of system tested: 1—shaped charge, 2—vinyl tube, 3—steel plates, 4—explosive tested.

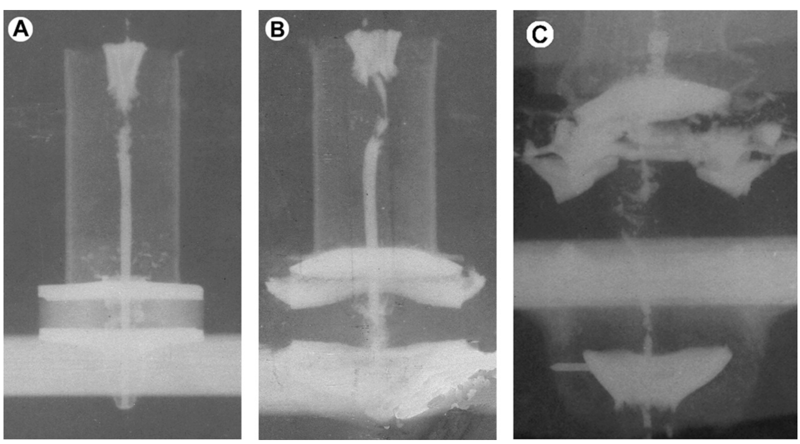

Figure 12. X-ray pictures of moving plates: A—CH50 explosive, charge C-2; B—CB explosive, charge C-2; C—CH50 explosive, charge C-1.

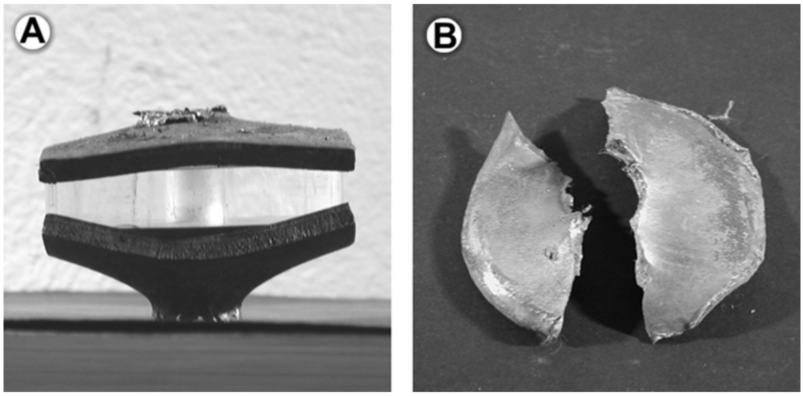

Figure 13. Recovered steel plates: A—CH50 explosive, charge C-2; B—CB explosive, charge C-2.

Chosen results of recording are shown in Figure 12. The jet generated by the shaped charge C-2 with a spherical liner initiates the detonation process in composition CB (B), but no detonation occurs in composition CH50 hit by this jet (A). The C-1 charge jet begins detonation in the explosive CH50 (C). Recovered steel plates from tests with compositions CH50 and CB are shown in Figure 13.

The results of jet initiation of the explosive tested are summarized in Table 5. For comparison, results of the test with pure NTO are also presented. The jet sensitivity of the mixtures with NTO is lower than that of composition CB.

Table 5
Results of jet initiation test (+ detonation, ± explosion, — no detonation)

	Explosive					
Charge	C30	C50	CH30	CH50	CB	NTO
C-1	+	±	+	+	+	—
C-2	—	—	—	—	++	—

Summary

New TNT/RDX/NTO and HMX/NTO formulations were successfully manufactured and characterized. Detonation performance and energetic characteristics of these mixtures are higher than or comparable with those of TNT/RDX (40/60) composition. The impact and jet sensitivity of tested formulations is lower than the sensitivity of the TNT/RDX mixture. New compositions can be considered as a suitable main charge filling to substitute for existing composition B.

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