Central European Journal of Energetic Materials
ISSN 1733-7178; e-ISSN 2353-1843

Cent. Eur. J. Energ. Mater., 2016, *13*(3), 592-611; DOI: 10.22211/cejem/65002

NTO-based Melt-cast Insensitive Compositions*)

Waldemar A. TRZCIŃSKI,* Joanna LASOTA,
Zbigniew CHYŁEK, Mateusz SZALA, Józef PASZULA

Military University of Technology,
Gen S. Kaliskiego 2, 00-908 Warsaw, Poland
E-mail: waldemar.trzcinski@wat.edu.pl

Abstract: This paper presents research on insensitive melt-cast explosive compositions based on 3-nitro-1,2,4-triazol-5-one (NTO) and containing TNT, wax, Al and RDX. The viscosity of the compositions in the operating temperature range was measured. Thermal analysis was performed as well as thermal stability and sensitivity to mechanical and thermal stimuli were tested. The detonation parameters were also determined. Finally, the acceleration ability (Gurney energy) and the JWL coefficients for the detonation products were established.

Keywords: NTO, insensitive explosives, melt-cast explosives

1 Introduction

Meltable secondary explosives are widely used in large calibre munitions, mainly because of the simplicity of forming the charges, and at the same time the possibility of recovering the material from out-of-use munitions. What is more, this type of material is relatively cheap and they are characterized by good detonation parameters. Conventional charges are formed by casting 2,4,6-trinitrotoluene (TNT) or its mixtures with hexogen (RDX) or octogen (HMX). Aluminium powder (Al) can be also added, when an increase in the destructive effect is desirable. Currently, a meltable component of castable compositions is 2,4-dinitroanisole (DNAN) [1, 2].

However, the simplest, and still used, meltable explosive is TNT. Nevertheless, one of its serious drawbacks is the significant increase in density on

---

*) Part of this paper was presented at the 18th Seminar on New Trends in Research of Energetic Materials, held in April 2015, Pardubice, Czech Republic

solidification. The effect of this phenomenon can be loosening of the solidified charge from the wall of a shell and formation of fissures and caverns inside the cast. To prevent this, small amounts of wax (usually natural wax, *e.g*. beeswax) is added which improves elasticity of the charge and prevents cracking at low temperatures and during shock loading.

Among melt-cast explosives based on TNT, the best known and the widest used is undoubtedly Composition B (Comp. B). In comparison to TNT, one merit of Comp. B is its relatively high detonation parameters, however a drawback is its much higher sensitivity to mechanical stimuli. Explosives containing TNT are effective and cheap, but excessively sensitive for current requirements (STANAG 4439 [3]). Cast TNT detonates after attack by a shaped charge, and typical mixtures of TNT with RDX or HMX (also aluminized ones) give full combat reaction in the not very demanding bullet impact test.

TNT is used for instance in low sensitivity compositions designated by the symbols XF® and XP®, recently elaborated in France. Those materials can contain 3-nitro-1,2,4-triazol-5-one (NTO), RDX or HMX in order to increase the detonation parameters. What is more, aluminium powder is also added when it is necessary to increase the destructive effect of the explosion. The composition XF®13333 (containing about 31% of TNT, 48% of NTO, 7.5% of wax and 13.5% of Al) has already been produced on a large scale and used in 155 mm artillery missiles. This munition received the NATO signature of insensitivity [4-7].

The aim of the present work was to obtain melt-cast compositions containing NTO with spheroidal particles and to test their properties. The method of obtaining spherically-shaped NTO is described in [8].

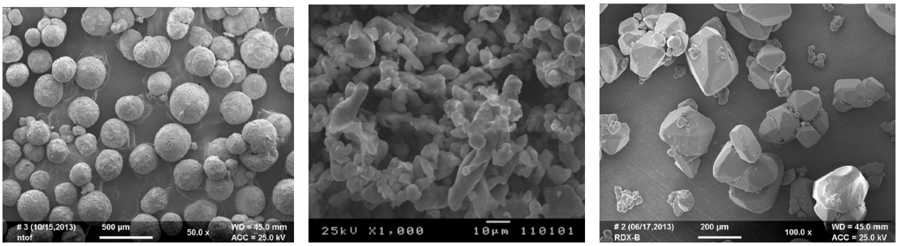
2 Characterization of the Components and Preparation of the Compositions

The components TNT, RDX and NTO were bought from NITRO-CHEM S.A. Company. NTO and RDX were recrystallized by the methods described in [8, 9].

To prepare the compositions, spheroidal NTO (Figure 1a) with particle diameter 75-350 mm (almost 99% of mass) was used. Its impact sensitivity, determined by the Bruceton method [10], was E_{50} = 61 J, while the friction sensitivity was more than 360 N. The bulk density was 1.049 g/cm^3.

A wax based on natural waxes with addition of thickeners and emulsifiers was used. Aluminium powder with a granularity of 325 mesh (Figure 1b) and bulk density 0.876 g/cm^3 was used.

The recrystallized RDX had rounded particles (Figure 1c). Its friction sensitivity was 165 N, while the impact sensitivity was E_{50} = 7.5 J. The bulk density was 1.09 g/cm^3.



a b c

Figure 1. SEM images of particles of (a) NTO, (b) Al, and (c) RDX.

The following compositions were chosen for testing:

CompNTO consisting of TNT (32%), NTO (48%), Al (12%), wax (8%), and
CompNTOR consisting of TNT (30%), NTO (37.5%), RDX (11%), Al (14%), wax (7.5%).

Measurements of the dynamic viscosity of the compositions in the liquid state were performed on a rotational viscometer made by Fungilab, model Expert R, equipped with a small sample adapter with an integrated heating mantle. Samples were heated by circulation of the heating medium in the heating mantle, using a laboratory thermostat (circulator). The appropriate amount of the sample was placed in the measurement tube and the spindle was turned on. When the temperature inside the sample was stable, the final temperature was adjusted on the circulator. The dependences of the viscosity on the temperature are shown in Figure 2.

CompNTOR has a lower viscosity than CompNTO. The viscosity of both compositions is much higher than that of TNT (11 cP at 85 °C), applied wax (66 cP), and a mixture of the wax with TNT (about 250 cP). However one should remember that both compositions contain more than 50% of solid components by mass. The range of the viscosity in the temperature range 85-95 °C guarantees proper castability of the compositions during the forming of the charges.

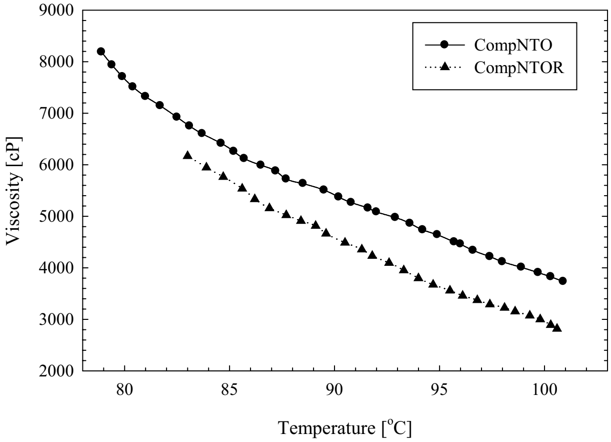
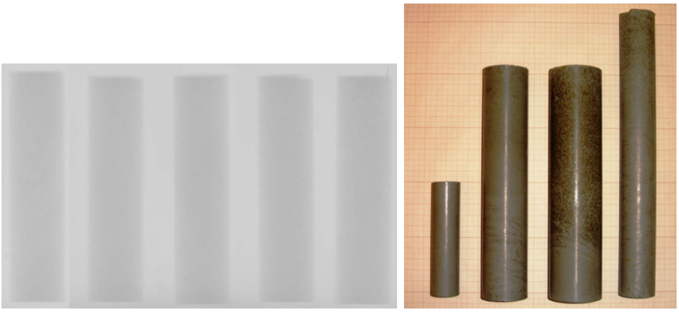


Figure 2. Dependence of the viscosity of CompNTO and CompNTOR on temperature.

To cast the compositions with NTO, the apparatus equipped with a mixer and a jacket heat exchanger was constructed. It served for the preparation of meltable explosive compositions, which after melting the matrix (TNT+wax), mixing and degassing, can be cast directly into moulds using a bottom vent. The mixer had a working capacity of 3.5 dm^3.

Casting was realized as follows: when the heating medium had reached a temperature of 90 °C, flaked TNT was introduced into the mixer. After complete melting of the TNT, heated wax in small portions was added, with vigorous mixing. A mixture of heated solid ingredients was slowly added to the prepared homogeneous mixture at a temperature of about 95 °C. The final composition was mixed less intensely, until it was homogeneous. Degassing was achieved with a vacuum pump. The composition was cast by partial opening of the vent in the bottom of the mixer. As a result of gravity, the composition poured from the mixer as a thin, continuous spout. The casts obtained were homogeneous.

The density of the cast charges of both compositions varied from 1.72 g/cm^3 to 1.74 g/cm^3. In order to confirm the lack of cavities inside the charges, X-ray photographs were taken. Typical photographs of CompNTO are shown in Figure 3.



a b

Figure 3. X-ray photographs of the CompNTO charges prepared for the gap test (a) and photographs of charges prepared for other tests (b).

3 Sensitivity

3.1 Sensitivity to mechanical stimuli

The impact sensitivity of the compositions was determined using a BAM apparatus with a 5 kg hammer. The height h_{50} in which the probability of initiation of an explosive is equal to 50% was determined by the Bruceton method [10]. In the main test, 30 trials were performed for each explosive. The cast explosives were initially crumbled and sieved. The fraction 0.5-1 mm was used.

The energies E_{50} corresponding to the h_{50} heights for CompNTO and CompNTOR were 49.5 J and 36 J, respectively. For comparison, E_{50} for flaked TNT is 38 J.

The friction sensitivity of the compositions was determined using a Julius-Peters apparatus, according to the standard PN-EN 13631-3 [11]. The fraction <0.5 mm was used. The friction sensitivity for CompNTO was more than 360 N, which shows that this material can be classified as insensitive to friction. For CompNTOR the sensitivity was 280 N (this value is the maximum frictional force at which no reaction was recorded in six consecutive trials).

3.2 Thermal sensitivity

The sensitivity to thermal stimuli of the compositions and their components was checked in Koenen tests [12], tube tests [13] and fast cook-off tests [12]. In the Koenen test, CompNTO turned out the least sensitive – the diameter of the hole in the container, when the explosive reaction of this composition took place, was 1 mm. In the case of CompNTOR this diameter was 2 mm, while in the case of cast TNT it was 4 mm. In STANAG 4491 [12] the value of 4 mm is given as the limiting orifice diameter for TNT.

In the tube tests, seamless steel tubes, with an internal diameter of 31.8 mm, wall thickness 6 mm and length 254 mm, were used. Two steel end-caps of thickness 10 mm sealed the tubes. A sample of the explosive, confined in the steel tube, was ignited by means of a 1.5 g charge of black powder. The degree of fragmentation of the tube was used to assess the relative explosiveness of the composition under test. The results of the thermal ignition test for CompNTO and cast TNT are shown in Figure 4.

a b

Figure 4. Results of the investigation on thermal ignition for (a) CompNTO and (b) cast TNT.

In the case of CompNTO, the tube was ruptured but one section remained intact. After the test, a small amount of unburned explosive remained in the tube. This observation corresponds to reaction category 1 (burning/decomposition) according to [12]. A similar effect was observed for a composition with 22% RDX (28% NTO, 29% TNT, 14% Al, 7% wax). In the test with cast TNT, the tube was ruptured into 3 fragments; their mass was equal to the total mass of the tube and end-caps. Moreover, 35 g of TNT (12% of initial mass) were recovered. The reaction of TNT to the thermal ignition was deflagration (reaction category 2).

The investigation of the sensitivity to fast heating by a flame for the compositions with NTO was carried out in accordance with a procedure of the cook-off test described in STANAG 4491 [12]. The explosives were cast into similar steel tubes as used in the tube test. The results of these cook-off tests are shown in Figure 5.


a b c

Figure 5. The results of the cook-off test for (a) CompNTO, (b) CompNTOR, and (c) cast TNT.

In the cases of CompNTO and CompNTOR, portions of unburned explosive were found in the tubes. After disruption, the tubes were ejected and were found next to the container. The response of both compositions to fast heating was category 1 – burning. The amount and the size of fragments obtained in the trial with TNT show that its reaction to heating was detonation.

A comparison of the response time of the tested explosives to heating is interesting. In the case of CompNTO and CompNTOR the reaction took place relatively fast, after 1.5 min and 2 min, respectively. This indicates a decomposition of one or more components, pressure increase and disruption of the tube. The latter prevents explosion of the tested composition. However, the response of TNT was observed after 5 min. This means that TNT was heated and melted, and its decomposition at a high temperature had an explosive nature.

3.3 Thermal stability and thermal analysis

The thermal stability of the compositions was determined according to the Polish Standard PN-V-04011-21 [14]. Two samples of each material were kept for two periods of 48 h at a temperature of 100 °C. After each stage, the samples were cooled to room temperature in a desiccator, and then weighed. The following results were obtained: the weight loss for CompNTO was 0.40% and 0.26% after the first and second stages, respectively, 0.48% and 0.24% for CompNTOR, and 0.38% and 0.36% for TNT. According to the standard [14], an explosive can be recognized as stable when its weight loss during heating is not more than 0.3%, unless a standard of an explosive is determined differently. The main ingredient of the tested compositions is TNT, which at 100 °C is molten and evaporates. This was confirmed by the result of the test on pure TNT, in which a total weight loss was 0.74% which is more than acceptable. Despite the fact that the samples were dried for 72 h at 50 °C just before the test, the weight loss of the tested compositions was greater during the first 48 h of heating, probably due to the evaporation of water enclosed inside the particles. No chemical reactions leading to a change in composition colour took place in the samples. Based on these results it can be claimed that CompNTO and CompNTOR are thermally stable.

Thermal analysis was carried out using a Labsys TG/DTA analyser according to the Standard PN-V-04011-21 [13]. The explosive samples weighed from 4 mg to 6 mg. The sample was heated at a rate of 2 K/min to 400 °C in an atmosphere of nitrogen passed at 50 mL/min. The TG/DTA curves for CompNTO are shown in Figure 6.

The characteristic effects for the 2 basic components of CompNTO are present on the thermogram. Transformation of the sample started at 78.7 °C and reaching the highest rate at 81.6 °C, corresponding with the melting of TNT, while a small endothermic effect starting in 186.2 °C corresponds with the evaporation of TNT. This process is accompanied by a loss of 34% of sample weight. Decomposition of the rest of the sample starts in 253.0 °C (with a weight loss of about 38%), which corresponds with the decomposition of NTO.

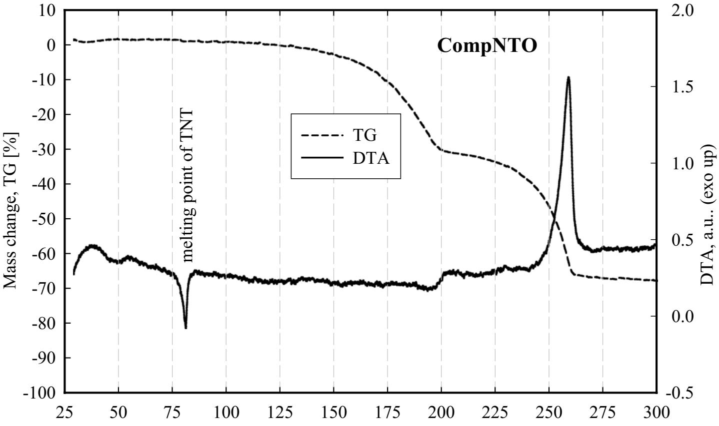


Figure 6. TG/DTA thermogram for CompNTO.

Changes in the composition CompNTOR were the start of melting of TNT at a temperature of 76.7 °C (Figure 7). The decomposition process of the sample began at a temperature of approx. 192 °C (the highest decomposition rate occurs at approx. 211 °C). The process began at a temperature close to the decomposition temperature of RDX, but the thermal effect is the sum of the heats of decomposition of both RDX and NTO (the latter decomposes at 257 °C in pure form). The loss in weight of the sample at this stage was approx. 45%. Then, an exothermic process, probably associated with the decomposition of NTO residues, starts at a temperature of approx. 240 °C. After this stage, the total weight loss of the sample was approx. 60%. For this sample, the endothermic effect of vaporization of TNT was obscured by the more powerful exothermic effect connected with the degradation of RDX and probably part of NTO.

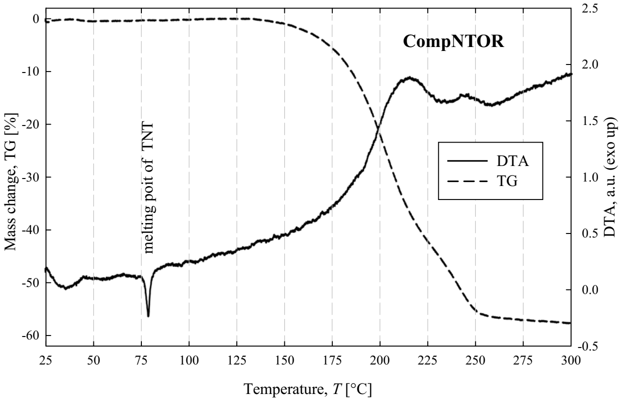


Figure 7. TG/DTA thermogram for CompNTOR.

3.4 Shock sensitivity

The shock sensitivity of the compositions was determined using the gap test. The tested explosive was cast into a copper tube having a 25 mm inner diameter and 2.5 mm wall thickness. The length of the charge was 100 mm. A donor charge of phlegmatized RDX (50 mm diameter, 157 g weight, 1.65 g/cm^3 density) served as a shock wave generator. From shot to shot, the length of a polyamide attenuator (100 mm in diameter) was changed. We recorded the highest and the lowest gap values at which complete detonation and failure to detonate were observed. The complete detonation of the explosive charge was indicated by a clean hole cut through the steel witness plate. The results of the gap tests are tabulated in Table 1.

Table 1. Results of the gap-tests for compositions with NTO and cast TNT

Explosive	Density [g/cm^3]	Thickness of the polyamide gap [mm]	
		detonation	no detonation
CompNTO	1.72	30	31
CompNTOR	1.73	39	40
Cast TNT	1.60	43	44

The results of the gap test indicate that the compositions with NTO are less sensitive to a shock wave than cast TNT. CompNTO is particularly less sensitive.

3.5 Bullet attack

The sensitivity to bullet attack was determined according to the Polish Standard PN-V-04027 [15]. This test assesses the response of confined explosive charges when subjected to the impact of a 12.7 mm antitank-incendiary bullet B-32. A sample of explosive was enclosed in a steel tube. The velocity of the bullet was 820 ± 60 m/s, and its weight was 46 g. The tested explosives were cast into seamless steel tubes with an internal diameter of 46 mm, wall thickness 4 mm and length 200 mm. Tubes were closed with steel end-caps of thickness 4 mm. Two trials were performed for each explosive. In the first trial, the shot was perpendicular, and in the second one parallel to the axis of the charge.

There was no reaction after the perpendicular shot for all tested explosives. The explosives remained in the tubes. The photographs of the tubes after the parallel shots are shown in Figure 8.

a b c

Figure 8. The tubes after parallel shots for (a) CompNTO, (b) CompNTOR and (c) cast TNT.

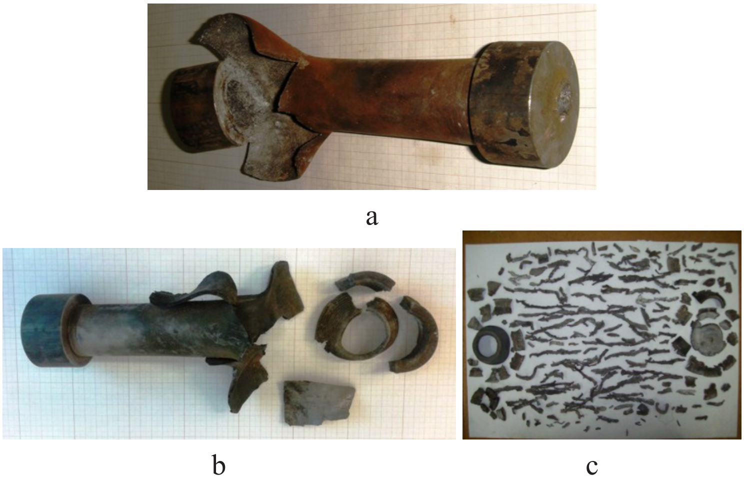
In the parallel shots, the bullet moves inside the explosive and in all cases punctures the tube before reaching the second end-cap. This can be evidence of a minimal declination of the shot line from the axis of the tube. In the case of CompNTO, almost all of the explosive remained in the tube (except for the part ejected by the bullet). Although the tube was ruptured, it can be said that there was no reaction of this composition to the bullet attack. The cause of the rupturing of the tube is the puncturing bullet and the increase of the pressure inside the explosive near to the end-cap closing the tube, as a result of reflection of the shock wave generated by the moving bullet. The top was unharmed and no traces of burning of the explosive were noticed.

After the parallel shot with CompNTOR, the remains of the explosive was observed in about half of the tube. A cylindrical fragment of the cap was pulled out, and inside the tube there were visible traces of burning. This is the evidence of a rise in pressure near the end-cap and deflagration of the composition. This process is quickly interrupted because of the violent decrease in pressure after pulling out the fragment and adiabatic cooling of the burning products. Similar phenomena were observed in the case of the TNT charge, but here no remains of the explosive were found in the tube. However, TNT was scattered on the walls of the bunker.

In accordance with the standard [15], only CompNTO is insensitive to attack of a B-32 bullet (category 0 reaction – no traces of chemical reaction), while the responses of CompNTOR and TNT is reaction of category 2 (pulling out of the cap fragment, about 20% of explosive consumed).

3.6 Jet attack

The reaction of the new compositions to a jet attack was studied by using a shaped charge made of 21.5 g pressed, phlegmatized HMX and a 14 g sintered copper liner with a cone-shape angle of 60° and base diameter of 32 mm. The estimated jet velocity was 5750 m/s. The tested explosives were placed in steel tubes of the sizes given for the tubes used in the tube tests, but the thickness of one of the end-caps was reduced to 6 mm. The jet hit this end-cap and was parallel to the axis of the charge.



a

b c

Figure 9. Photographs of tubes after the jet test for (a) CompNTO, (b) CompNTOR, and (c) cast TNT.

Photos of the tubes after the tests are shown in Figure 9. In the case of CompNTO there were no clear indications of chemical reaction, the jet did not initiate a reaction in the explosive. Disruption of the tube from the side opposite to the jet impact was caused by reflection of the strong shock wave, generated by the tip of the jet from the top. The explosive was scattered in sand filling a steel container. It can be assumed that the response of this composition for shaped charge attack is ‘no reaction’. In case of the CompNTOR we observed an initiation of a deflagration process in the material by the shaped charge jet. In this case, the tube was ruptured from the side of the impact of the shaped charge jet. The amount of fragments after the trial with TNT shows that detonation took place after impact of the shaped charge jet.

4 Performance

The detonation parameters of compositions with NTO and cast TNT were determined in the plate dent test. In this test, cylindrical charges of about 40 mm in diameter and 200 mm height were used. Each charge was cast into a steel tube of 39.6 mm internal diameter, and then removed from the tube. To initiate detonation, a 50 g charge of phlegmatized RDX (40 mm in diameter, density 1.645 g/cm^3) was used. The detonation velocity D was measured by using 2 short-circuit sensors. The first one was 25 mm away from the bottom of the charge, and the second was 70 mm away. The depth h of the crater in the steel plate was measured after the test. The detonation pressure at the Chapman-Jouguet point, p_{CJ}, was determined from the earlier established calibration relation between h and p_{CJ}. The results of these tests are tabulated in Table 2. Also given in the table are parameters calculated using the CHEETAH thermochemical code [16], with a set of parameters BKWC for the BKW equation of state for detonation products. In the calculations, the chemical inertness of aluminium was assumed.

Table 2. Plate dent test results

Explosive	ρ_0 [g/cm^3]	h [mm]	$p_{CJ\text{-}exp}$ [GPa]	$p_{CJ\text{-}cal}$ [GPa]	D_{exp} [m/s]	D_{cal} [m/s]
CompNTO	1.73	-	-	16.70	-	6763
CompNTOR	1.74	5.74	19.1	17.91	7190	6945
Cast TNT	1.61	6.07	20.1	18.12	6820	6729

CompNTO did not detonate under the conditions of the plate dent test. This means that the critical diameter of this composition is greater than 40 mm. When a metal casing was used, CompNTO detonated in charges with 25 mm diameter. From the test it follows that the critical diameter of CompNTOR is lower than 40 mm. The brisance and detonation pressure of CompNTOR are slightly lower than the same parameters determined for cast TNT.

The measured detonation velocity and pressure for the compositions tested were greater than those calculated parameters assuming inert aluminium. However the calculated detonation pressure for CompNTOR assuming aluminium reactivity was 19.61 GPa and slightly higher than determined experimentally.

The detonation velocity of the new compositions was also measured in the cylinder test using the short-circuit sensors. The cylinder test results were also the basis for the determination of the acceleration abilities of the detonation products. The copper tube was 250 mm long with an internal diameter of 25 mm and wall thickness 2.5 mm. The compositions were cast directly into the tubes. The process of acceleration of a copper tube by the detonation products was recorded with an impulse X-ray apparatus.

The detonation velocities measured in the cylindrical test and calculated with the CHEETAH code are compared in Table 3.

Table 3. Detonation velocities of the tested explosives measured in the cylinder test and calculated

Explosive	ρ_0 [g/cm^3]	D_{exp} [m/s]	D_{cal} (Al inert) [m/s]	D_{cal} (Al active) [m/s]
CompNTO	1.73	6720	6763	6627
CompNTOR	1.74	6910	6945	6757
Cast TNT	1.60	6730	6705	

The experimental detonation velocities determined for the compositions with NTO correlate well with the velocities calculated with the assumption of inert Al. This means that aluminium does not take part in the chemical reactions proceeding in the reaction zone of the detonation wave.

Using the method described in [17], the dependence of the tube velocity on the relative volume of the detonation products was determined (Figure 10). For comparison, the velocities of the tubes calculated with the CHEETAH code were also plotted on the figures. The calculations were performed assuming total chemical inertness of the aluminium powder in the detonation products and reactivity of the aluminium.

The acceleration ability of an explosive can be described by the so-called Gurney energy, which is defined as the sum of the kinetic energies of the driven tube and detonation products. The dependences of the Gurney energy of the compositions considered here, related to unit mass and unit volume of explosive, on the relative volume of the detonation products are shown in Figure 11. From Figure 11a it follows that the acceleration ability of the compositions with NTO (the final value of the Gurney energy being about 2660 kJ/kg) is lower than that of cast TNT (2900 kJ/kg). One should remember that the Gurney energy in this case is related to a unit mass of explosive. However, the mass of the filling in a shell with the same volume depends on the density of the explosive used, thus the Gurney energy related to unit volume should be compared (Figure 11b). The results from Figure 11b indicate that the acceleration ability (defined as the final value of the Gurney energy) of the compositions with NTO are similar to that determined for cast TNT.

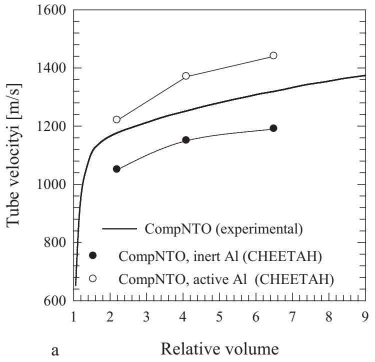


Figure 10. Dependence of the tube velocity on the relative volume of the detonation products for (a) CompNTO and (b) CompNTOR.

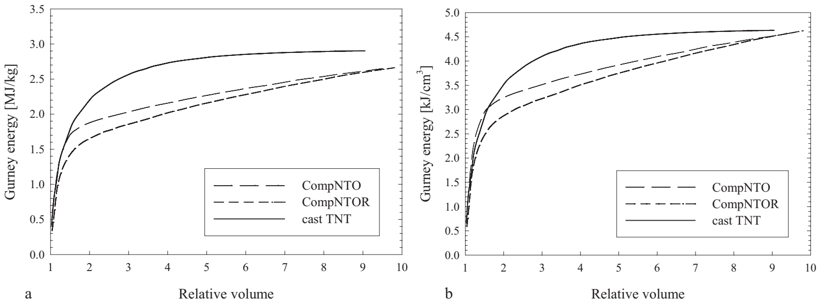


Figure 11. Dependence of the Gurney energy related (a) to a unit mass of explosive, and (b) to a unit volume of explosive, on the relative volume of detonation products.

The calorimetric heat of detonation of the tested compositions was measured using the method described in [18]. The melt-cast explosives were crushed and pressed. Pellets of mass 20 g and diameter 25 mm were detonated in a spherical bomb having a volume of 5.6 dm^3. The bomb was filled with argon at a pressure of 2.0 MPa. Two tests were conducted for each explosive. The maximum deviation in the determination of the heat of detonation was 1.5%. The values of the calorimetric heat were 3350 and 4000 J/g for CompNTO and CompNTOR, respectively. The heat determined for CompNTOR is slightly lower than that measured for TNT, which ranges from 4019 J/g [19] to 4430 J/g [20]. However the heat of detonation for CompNTO is much lower than that for TNT. This is probably due to the large critical diameter of this composition, an explosion of a charge takes place in a bomb calorimeter, not its detonation.

5 JWL Equation of State

Jones, Wilkins and Lee proposed the equation of the isentrope for the detonation products of explosives in the following form:

$$p = A\mathrm{e}^{-R1V} + B\mathrm{e}^{-R2V} + CV^{(-1-\omega)} \tag{1}$$

where A, B, C, R_1, R_2 and ω are constants for a given explosive, p pressure, v specific volume, $V = v/v_0$, $v_0 = 1/\rho_0$. The following equation of state (JWL EOS) corresponds to this isentrope:

$$p = A\left(1-\frac{\omega}{R_1 V}\right)\mathrm{e}^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)\mathrm{e}^{-R_2 V} + \frac{\omega E}{V} \tag{2}$$

The basic method of determination of these coefficients uses the results of the cylinder test. Additionally, some relations between coefficients, which follow from the conservation laws written for the CJ point, are used in this method [21]. As a result, parameters A, B, and C are expressed as functions of R_1, R_2, ω and ρ_0, D, p_{CJ} and the detonation energy E_0. The initial density and the detonation velocity D are established in the cylinder test.

The detonation pressure for CompNTOR was determined in the plate-dent test in this work. However, the pressure for CompNTO could not be measured. In order to estimate the detonation pressure the results of the cylinder test were used. Analysis of the data contained in [21, 22] shows that the angle of inclination of the real isentrope of the expansion of the detonation products, presented in the plane of the specific volume-pressure on a logarithmic scale, is close to the angle of a line that represents an isentrope with constant exponent γ when the change in the relative volume of the product does not exceed 4. The so-called effective exponent of the isentrope determined on the basis of the cylinder test results for this range of volume change was used to estimate the detonation pressures of the tested explosives. The effective exponent of the isentrope was determined by comparison of the experimental profile of the copper tube with that obtained from numerical modelling of the expansion process [23]. The detonation products, driving the tube, are described by the constant-γ equation of state. Typical experimental and calculated profiles of the copper tube driven by the detonation products of CompNTO are presented in Figure 12.

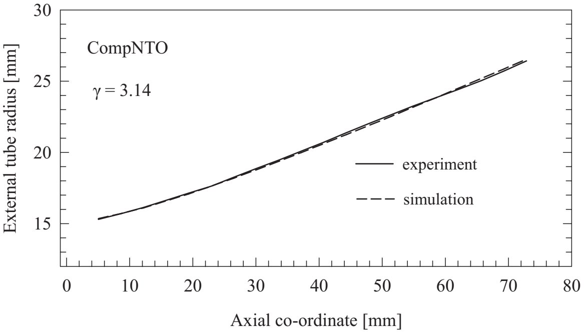


Figure 12. Experimental and calculated profiles of a copper tube driven by the detonation products of CompNTO.

A satisfying conformity of experimental and theoretical profiles was achieved when the values of γ were 3.14, 3.49 and 2.87 for CompNTO, CompNTOR and cast TNT, respectively. The detonation presure was then calculated from the relation:

$$p_{CJ} = \frac{\rho_0 D^2}{\gamma + 1} \tag{3}$$

The detonation pressures estimated in this way were 18.9, 18.5 and 18.7 GPa for CompNTO, CompNTOR and cast TNT, respectively. In the calculation procedure for the JWL coefficients, the mean values of the pressures determined in the plate-dent test and from the cylinder test were used (Table 4).

As the heat of detonation measured in a calorimetric bomb for the new compositions may be understated, the results from the cylinder tests were used to estimate the detonation energy. In [16] it was shown that there was a correlation between the velocity of the driven tube at a given volume of the detonation products and the detonation energy of an explosive. In the present work, cast TNT was used as a reference explosive with detonation energy E_0 = 7.1 GPa. The estimated detonation energies for CompNTO and CompNTOR are given in Table 4.

Table 4. Data used in the procedure for calculation of the JWL parameters

Explosive	ρ_0 [g/cm^3]	D [m/s]	p_{CJ} [GPa]	E_0 [GPa]
CompNTO	1.73	6720	18.9	7.06
CompNTOR	1.74	6910	18.8	7.06
Cast TNT	1.60	6730	19.4	7.1

If the parameters ρ_0, D, p_{CJ} and E_0 are known, only the constants R_1, R_2 and ω remain to be determined. These were calculated by the method in which the experimental dependence of the radial displacement of the outer tube wall on the axial co-ordinate is compared with that obtained from numerical simulations [21, 24]. The set of JWL coefficients was chosen for which the experimental and the calculated displacements are sufficiently close to each other. Typical experimental and calculated profiles of the copper tube driven by the detonation products of CompNTOR are presented in Figure 13.

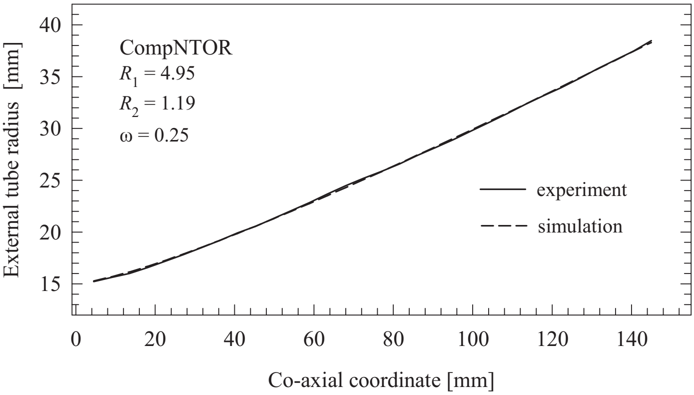


Figure 13. Experimental and calculated profiles of a copper tube driven by the detonation products from CompNTOR described by the JWL EOS.

The calculated values of the JWL coefficients are presented in Table 5. Figure 14 displays the JWL isentropes determined. They can be used, for example, in calculating the expansion work of the detonation products, blast wave characteristics in air or shock wave parameters in a medium surrounding an explosive charge.

Table 5. JWL coefficients for the detonation products of the explosives tested

Explosive	*A* [GPa]	*B* [GPa]	*C* [GPa]	R_1	R_2	ω
CompNTO	589.1016	7.127724	0.8685490	4.84	1.30	0.22
CompNTOR	735.3798	3.127510	1.152393	4.95	1.19	0.25
Cast TNT	384.2007	7.211705	0.8570273	4.42	1.18	0.25

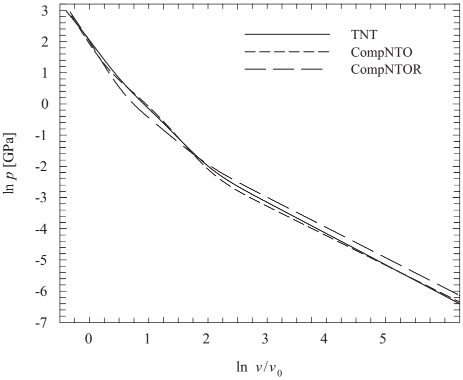


Figure 14. The JWL isentropes for the detonation products of the explosives tested.

6 Conclusion

The new compositions CompNTO and CompNTOR were characterized with good rheological properties, so they can be cast on a large scale at a temperature less than 100 °C. The sensitivity of the compositions, especially CompNTO, to a bullet attack, jet attack, shock wave and fast heating is lower than the sensitivity of cast TNT. The detonation parameters of CompNTO are slightly lower, and the parameters of CompNTOR are a bit higher, than those of cast TNT.

Based on the results of the sensitivity tests performed and on the detonation parameters, it can be ascertained that CompNTO fulfils the requirements set for explosives destined for insensitive munitions.

References

[1] Ravi P., Badgujar D.M., Gore G.M., Tewari S.P., Sikder A.K., Review on Melt Cast Explosives, *Propellants Explos. Pyrotech.*, **2011**, *36*, 393-403.

[2] Trzciński W.A., Cudziło S., Dyjak S., Nita M., A Comparison of the Sensitivity and Performance Characteristics of Melt-pour Explosives with TNT and DNAN Binder, *Cent. Eur. J. Energ. Mater*., **2014**, *11*(3), 443-455.

[3] STANAG 4439 (Edition 3) – *Policy for Introduction and Assessment of Insensitive Munitions (IM)*, NATO, **2010**.

[4] Weckerle A., Coulouarn C., A Step Further for the XF® Explosive Family Dedicated to Insensitive Munitions (IM), 2*010 Insensitive Munitions & Energetic Materials Technology Symposium*, Munich, Germany, **2010**.

[5] Coulouarn C., Boulanger R., Bouchaud D., XP®: A Cost Effective Approach for Medium Calibre Insensitive Munitions (IM), *2010 Insensitive Munitions & Energetic Materials Technology Symposium*, Munich, Germany, **2010**.

[6] Aumasson R., Insensitive Munitions® Using Fusible and Pressable Explosives, *WAT-NEXTER-NITROCHEM Conference*, Warsaw, **2011**.

[7] Spyckerelle C., Songy C., Eck G., IM Melt Cast Compositions Based on NTO, *2010 Insensitive Munitions & Energetic Materials Technology Symposium*, Munich, Germany, **2010**.

[8] Lasota J., Chyłek Z., Trzciński W.A., Methods for Preparing Spheroidal Particles of 3-Nitro-1,2,4-triazol-5-one (NTO), *Cent. Eur. J. Energ. Mater*., **2015**, *12*(4), 769-783.

[9] Szymańczyk L., Maranda A., Nowaczewski J., Modification of the Properties of RDX, *3rd Int. Armament Conference*, Waplewo, Poland, **2000**.

[10] STANAG 4489 (Edition 1) – *Explosives, Impact Sensitivity Test*, NATO, **1999**.

[11] *Explosives for Civil Use – High Explosives – Determination of Sensitiveness to Friction of Explosives*, Polish and European Standard PN-EN 13631-3, **2004**.

[12] STANAG 4491 (Draft 3/98), *Explosives, Thermal Sensitiveness and Explosiveness Tests*, NATO, **1998**.

[13] Tube Test – Internal Ignition, in: *Energetic Materials Testing and Assessment Policy Committe*e, *Manual of Tests*, Defence Ordnance Safety Group, **2005**.

[14] *Military High Explosives – Test Methods – Determination of Stability*, Polish Standard PN-V-04011-21, **1998**.

[15] *Explosives and Products Containing Explosives – Determination Method of Sensitivity for Projectile Impact*, Polish Standard PN-V-04027, **2001**.

[16] Fried E., CHEETAH 1.39 – *User's Manual*, Lawrence Livermore National Laboratory UCRL-MA-117541 Rev. 3, **1996**.

[17] Trzciński W.A., Application of a Cylinder Test for Determining Energetic Characteristics of Explosives, *J. Techn. Phys.*, **2001**, *42*(2), 165-179.

[18] Kiciński W., Trzciński W.A., Calorimetry Studies of Explosion Heat of Non-ideal Explosives, *J. Therm. Anal. Calorim*., **2009**, *96*(2), 623-630.

[19] Cudziło S., Trębiński R., Trzciński W.A., Wolański P., Comparison of Heat Effects of Combustion and Detonation of Explosives in a Calorimetric Bomb Filled with Inert Gas or Air, *Biuletyn WAT*, **1998**, *47*(11), 33-48.

[20] Trzciński W.A., Paszula J., Cudziło S., Experimental and Theoretical Estimation of the Afterburning Heat of Detonation Products in a Calorimetric Bomb, *Biuletyn*

WAT, **2000**, *49*(12), 66-75.
[21] Trębiński R., Trzciński W.A., Determination of an Expansion Isentrope for Detonation Products of Condensed Explosives, *J. Techn. Phys*., **1999**, *40*(4), 447-456.
[22] Trzciński W.A., Cudziło S., The Application of the Cylinder Test to Determine the Energy Characteristics of Industrial Explosives, *Arch. Mini. Sci.*, **2001**, *46*(3), 291-307.
[23] Cudziło S., Trębiński R., Trzciński W.A., Determination of the Effective Exponent of Isentrope for the Detonation Products of High Explosives, *Chem. Phys. Reports*, **1997**, *16*(9), 1719-1732.
[24] Trębiński R., Trzciński W.A., Modelling of the Process of Driving a Cylindrical Tube by the Detonation Products Described by the JWL Equation of State, *J. Techn. Phys*., **1997**, *38*(4), 783-797.