Additional properties studies of DNAN based melt-pour explosive formulations

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The good Insensitive Munitions tests results observed with Dinitroanisole (DNAN) and Nitrotriazolone (NTO) based melt-pour explosive formulations during different projects such as US Army project CLIMEx (Common Low-cost IM Explosive) and GD-OTS / NAMMO project on 120mm IM HE-T has increased the interest towards this type of formulations for different types of guns and tube fired ammunition. Along with their reduced sensitivity, these formulations provide the ability to use standard TNT based explosive melt-pour process equipment and keep the associated high level of production. At the last IM/EM symposium in Tucson, GD-OTS Canada presented preliminary processing studies and some physical properties of two of these formulations developed by BAE Systems OSI: OSX-7 (now designated as IMX-104) and OSX-8 (now designated as PAX-48). Along with DNAN melting matrix, both formulations contain NTO as the main energetic filler with RDX for the first formulation and HMX for the second one. This paper will present the results of additional studies performed with these formulations. This will include detonation performance data and some additional IM small scale Variable Confinement Cook-off test (VCCT) at a different heating rate. The results of bullet impact test on 105mm M1 projectiles filled with these formulations will also be presented. The results presented will be compared with TNT based explosive and the properties values will be given relative to composition B.

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1. INTRODUCTION

Many melt-pour insensitive high explosive formulations have been developed over the past ten years and among them the formulations based on Dinitroanisole (DNAN) and Nitrotriazolone (NTO) mixed with other ingredients presented good standing to IM tests performed during different projects such as US Army project CLIMEx (Common Low-cost IM Explosive) for artillery and mortar ammunitions [1, 3] and GD-OTS / NAMMO 120mm IM HE-T project [4]. The results from these programs indicated that this family of melt-pour formulations could provide results matching those of cast-cure or pressed explosives. The possibility of using already available TNT-based melt-pour process equipment in North American industrial base with minimal reduction on the final production output as well as the fact that they are relatively easier to demilitarize were viewed as advantages for these formulations.

GD-OTS Canada, formerly known as SNC TEC, has developed expertise in the area of filling of projectiles with melt-pour explosives for more than sixty years using conventional TNT (trinitrotoluene) based formulations. The expertise with dinitroanisole (DNAN) based formulations was first gained from working with the PAX-21 and PAX-25 formulations developed by ATK Thiokol during contracts with the US Government [5] then from internal programs working with PAX-34 and PAX-33, originally developed by BAE Systems Holston under the names OSX-3 and OSX-1 [6]. Building on this expertise, GD-OTS Canada has put in place an internal R&D program aimed at the characterization of the various aspects of IM melt-pour explosive formulations to have the knowledge to quickly respond to customer requests for application in various munitions [7]. At the last IM/EM symposium in Tucson AZ, data obtained from the studies performed with OSX-7 and OSX-8 formulations developed by BAE OSI Holston Army Ammunition Plant (HSAAP) [8] was presented. This work covered processing variables, filling of 105mm M1 shells, some physical properties and Variable Confinement Cook-off Tests (VCCT) results. This paper presents additional results covering detonation performance, bullet impact tests performed on 105mm M1 filled projectiles and additional VCCT results obtained with these formulations whose names have been changed to IMX-104 and PAX-48 respectively.

2. EXPERIMENTAL

2.1 Material Description

General data on the IMX-104 formulation composition previously known as OSX-7 and PAX-48 previously known as OSX-8 formulations are presented in Table I below. The composition B formulation description is also included in the table because it is considered as the reference material in most of our studies.

Table I: General description of the formulations tested

FORMULATION NAME	IMX -104 (OSX-7)	PAX-48 (OSX-8)	Composition B
Ingredients	DNAN NTO RDX	DNAN NTO HMX	59.5% RDX 39.5% TNT 1% Wax

2.2 Detonation performance studies

As mentioned above, GD-OTS Canada first studies to gain knowledge were aimed at the processing and some physical properties of the IMX-104 and PAX-48; which were still relatively

new at that time. Building on this knowledge, it was considered that the next logical step was to study the detonation performance data of these formulations in order to confirm their capabilities in munitions since the available results were variable and surprising in some cases. Some of these data had been obtained with computer simulations using the Cheetah thermochemical code so it was also desired to validate the ability of this computer code to provide dependable results with this type of formulations since some of the factors used in the calibration of this code are based on TNT and RDX. Previous studies conducted by other organizations and in GD-OTS Canada indicated that this code could be used efficiently with formulations as different from the TNT based explosive as the HTPB based cast cure explosives or pressed formulations with some adjustments to define the polymeric matrix. Some limitations on the capabilities of Cheetah to compute reliable values for the DNAN based explosives due to the nature of the formulations had been mentioned however. The studies were started with the simulations of PAX-21 and PAX-25 and the comparison with experimental data of detonation velocities and Gurney coefficient obtained with these formulations in previous studies [5]. This work was conducted as part of internal studies aimed at the validation of version 5.0 of the Cheetah code [9] with various types of explosive formulations. Different equations of states and data libraries are available with that version of the code but the conclusion from that study indicated that the Becker-Kistiakowski-Wilson (BKW) equation of state and the library calibrated for Cheetah (BKWC) produced overall results closest to the experimental data for this type of explosive [10]. The simulation values were typically within 10% of the experimental values which led to the preliminary conclusion that acceptable results could be obtained so values were computed for IMX-104 and PAX-48.

Five computation methods to obtain the Gurney coefficient or velocity ($\sqrt{2E}$) were evaluated as part of GD-OTS Canada study on this subject [10] and the results showed that Equation (1) presented by Danel and Kazandjian in the Propellant, Explosives and Pyrotechnics journal provided values closest the one obtained experimentally with cylinder test [11].

$$\sqrt{2E} = \sqrt{\frac{D_{CJ}^2}{\left(\gamma_{CJ}^2 - 1\right)} \left[1 - 2 \left(\frac{\rho}{\rho_0}\right)^{\gamma_{CJ}-1} \left(\frac{\gamma_{CJ}}{\gamma_{CJ}+1}\right)^{\gamma_{CJ}} \right]} \qquad (1)$$

In this equation, D_{CJ} is the detonation velocity a the Chapman-Jouguet (C-J) point, γ_{CJ} is the ratio between heat capacities at constant pressure and constant volume, ρ_0 is the initial velocity and ρ is the density at the point of interest. The point of interest for this study is the terminal value where the volume of the cylinder was increased by a factor of seven or ρ/ρ_0 is equal 0 0.1428. The D_{CJ} and γ_{CJ} used were obtained with the Cheetah code.

The detonation velocities, pressures and Gurney coefficient ($\sqrt{2E}$) results will be discussed in Section 3.1 below.

Along with these computed values, it was desired to conduct experimental determination of the detonation velocity and pressure for the formulations of interest so testing methods were reviewed and further discussed with Mr Patrick Brousseau from DRDC Valcartier and Mr. Jean Beaupré from METC Valcartier who have long experience with conducting such tests [12]. The detonation pressure was obtained by an indirect method using the plate data method [13]. Both values could be obtained during the same test. The tests were conducted at Mining Engineering Resources Limited (MREL) Kinburn site using the set-up illustrated in Figure 1. The tested sample was a cylinder of 5.1 cm (2") diameter by 25.5 cm (10") long. It was detonated with a Dyno Nobel electric Super SP detonator mounted on a 3.2 cm (1.25") diameter by 1.6 cm (0.625") thick composition A5 booster pellet encased in an aluminum holder to ensure centering

of these elements on the test sample. Each test sample was fitted with three ionization probes mounted inside the samples, at 5 mm (0.2") from the wall, located at 1.0 cm (0.4"), 6.1 cm (2.4") and 11.2 cm at (4.4") from the end away from the initiation point to obtain detonation velocity. Three values of detonation velocity were obtained from each test. The explosive sample and its ancillary equipment were mounted on three AISI 1018 plates with 15 cm (6") x 15 cm (6") x 5.1 cm (2") thick dimensions which were further set on four (4) backing steel plates of 45cm (18") x 45cm (18") x 5.1 cm (2") thick steel and on a leveled steel base plate of 90cm (36") x 90cm (36") x 2.5cm (1") thick. The plate dent was measured on the top AISI 1018 plate using a depth micrometer with a 1.9 cm (0.75") ball and 1.9 cm (0.75") ring as described in reference [13]. Three tests were conducted with IMX-104 and PAX-48 as well as well as with composition B; the latter being used as the reference to determine the detonation pressure from the plate dent.

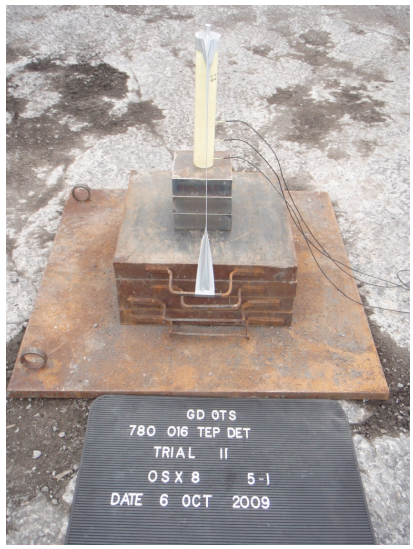


Figure 1: Detonation velocity and plate dent test set-up

2.2 Bullet Impact Test

As part of the planned studies on the IMX-104 and PAX-48 formulations, it was desired to conduct IM tests. A review of possible tests led to the selection of bullet impact as the first test to be accomplished in this program. This test was conducted by GD-OTS Canada Nicolet group as per the STANAG 4241 ed. 2 [14] using 0.5 cal APM2 bullets on bare 105mm M1 filled projectiles with an inert plug representing fuze. The general test set-up is illustrated in the left picture of Figure 2. A 36" 0.5 cal Mann barrel mounted on a mobile carriage and fitted with a solenoid to perform remote control firing was used to perform these tests. This gun is shown in the center picture of Figure 2 along with the protection system and the velocity screen system to obtain the bullet velocity. The gun muzzle was located at 7.6m (25') from the test item. The right side picture in Figure 2 shows the 105mm M1 test item standing on a 30cm (12") square x 2.54 cm (1") thick low carbon steel witness plate on 1.5m stand. A 60cm (24”) x 40cm (16”) x 2.54cm (1") thick low carbon steel is used as side witness plate. Two rows of three pencil type blast gauges manufactured by PCB Piezotronics mounted at 90° from each other were used to take blast overpressure measurements from these tests. The three gauges in each series were located at 6.1m (20'), 12.2m (40'), 18.3m (60') from the test item. The tests results were evaluated according to STANAG 4439 [15] and MIL-STD-2105C [16]. Two tests were performed with the composition B baseline and for each of the two explosives of interest, IMX-104 and PAX-48.

Figure 2 – Bullet impact set-up and views of some equipment

2.3 Variable Confinement Cook-off Test (VCCT)

The Variable Confinement Cook-off Test (VCCT) is a good small scale test to compare explosives and eventually to get an idea of the capability of a formulation to withstand the IM Cook-off tests. Furthermore, since the test geometry is simple, one can easily perform computer simulations in view of obtaining data for the eventual simulation of the full system of interest; which is an eventual goal of GD-OTS Canada work in this area. The experimental results on the explosives of interest coming from tests conducted at DRDC Valcartier using intermediate heating rate (25°C/hr or 45°F/hr) were presented at the last IM/EM symposium in Tucson [6]. The aim of a parallel study to this program was the acquisition by GD-OTS Canada of the capabilities to run the VCCT test in-house. The first step was the review of the equipment and procedure to conduct the test at different heating rates as described in STANAG 4491 [17]. It was desired to be able to conduct both slow/intermediate heating rate version of the test as well as the fast rate version. In a first approach, the heating systems described in the STANAG was acquired and tested. In order to have a comparison point, intermediate heating rate (25°C/hr or 45°F/hr) was tested and the results were compared to those obtain at DRDC Valcartier. Following the review of the results and discussion with people from this organization to clarify some issues, a heating band made of heating wires embedded in a rubber type material was found to provide more reliable heating which is important for slower heating rates. Different heating wire set-ups were tested to conduct fast cook-off and obtain the curve presented in reference [17]. The drawing of the general VCCT set-up used is illustrated in the left side of Figure 3 below. The center picture shows the slow/intermediate cook-off arrangement while the one right side picture shows the fast cook-off test set-up Two thicknesses of confinement have been tested so far: 0.39mm (0.0155") and 1.14mm (0.045") with two tests were done for each explosive.

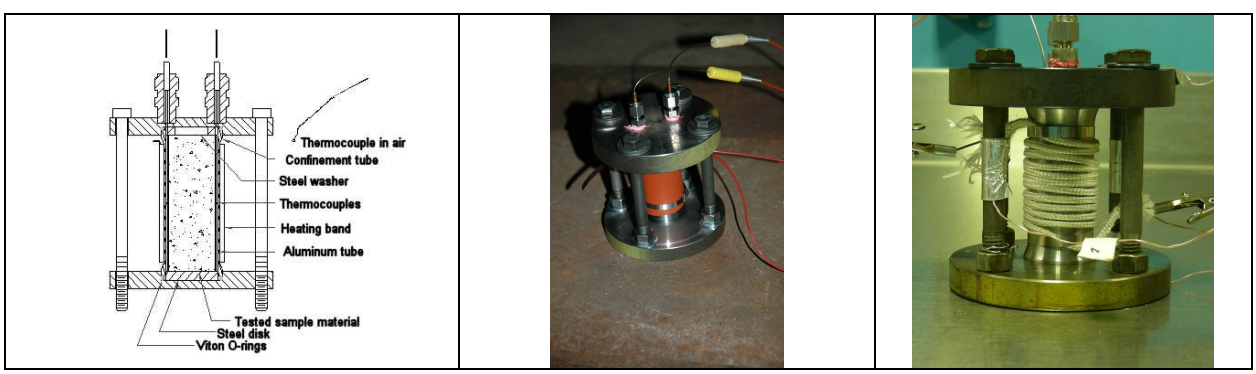


Figure 3 – VCCT set-up

3. RESULTS AND DISCUSSION

3.1 Detonation performance

The results obtained from both the Cheetah 5.0 simulations and the experimental results are summarized in Table II below. The results are presented as the percentage of composition B. Data on the exact explosives formulations compositions obtained from BAE OSI for the IMX-104 (OSX-7) and PAX-48 (OSX-8) and the measured density of the cylinders prepared for the experimental tests were used in the Cheetah 5.0 simulations. Composition B manufactured by GD-OTS Canada Valleyfield was used for the tests and the data from the chemical analysis and density measurements were used to perform the computations.

Table II: Detonation performance results

Properties \ Formulations	IMX-104 (OSX-7)	PAX-48 (OSX-8)
Detonation velocity (computed)	92.4%	91.2%
Detonation velocity (experimental)	94.4%	92.6%
Detonation pressure (computed)	82.8%	79.5%
Detonation pressure (experimental)	81.5%	82.8%
Gamma CJ (computed)	102.0%	101.9%
Gurney coefficient ($\sqrt{2E}$) (computed)	90%	88%

The results show that both IMX-104 and PAX-48 are less energetic than composition B which could be expected considering that DNAN is less powerful than TNT and NTO provides less energy than RDX. The properties of both formulations are close to each other with IMX-104 being slightly more powerful than PAX-48. The Gamma CJ data are presented because they are used to compute the Gurney coefficient using Equation 1. Some indications from fragmentation tests in ammunition seemed to indicate that the properties of the IMX-104 and PAX-48 could be closer to composition B than indicated by the computed results, so it is planned to perform cylinder tests to confirm the results.

3.2 Bullet impact tests

The set-up described in section 2.2 was used to perform bullet impact tests. Standard composition B filled 105mm M1 was tested twice to provide a baseline. A picture of the set-up after the test from one of the experiment is shown in the left side picture of Figure 4 while the right side picture present the side witness plate. Although the size of the fragment appears to be big and the bottom witness plate is not punched, the measured blast overpressure from the blast gauges compared to the curve obtained from the static detonation of a composition B filled 105mm shell and the film record from the high speed camera led to the conclusion that a Type I or II reaction was obtained. A Type V reaction was obtained for the bullet impact tests conducted on all the projectiles filled with either IMX-104 or PAX-48 filled explosives. Pictures of the test set-up and recovered projectiles showing the full projectile as well as bullet entrance and exit holes are presented in Figure 5 for IMX-104 and Figure 6 for PAX-48. No pressure was recorded by the blast gauges in any of these tests which is a additional proof of the reaction type mentioned. Some flames were visible on the high speed camera recording as will be shown in the presentation but it was very short in duration and only a limited amount of explosive material was burned.

Figure 4 – Test set-up and side witness plate after composition B bullet impact test

Figure 5 – Test set-up and recovered projectile from IMX-104 (OSX-7) bullet impact test

Figure 6 – Test set-up and recovered projectile from PAX-48 (OSX-8) bullet impact test

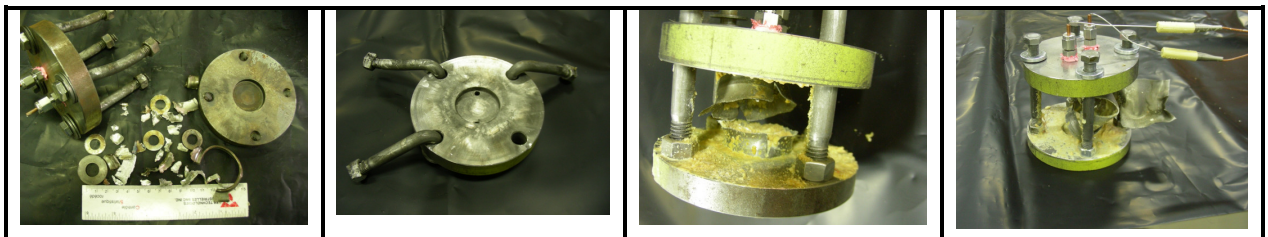
3.5 Variable Confinement Cook-off Tests

Table III and Figure 8 below presents the results of the VCCT conducted at an intermediate heating rate of 25°C/hr or 45°F/hr. The reaction temperatures obtained during the series of tests performed in GD-OTS Canada test site are very similar to those obtained at DRDC Valcartier for composition B and IMX-104 but it is lower by about 10°C (18°F) for PAX-48. The reaction levels were evaluated according to section 5 of reference [17]. Stronger types of reaction as evaluated according to the definitions were obtained with composition B with GD-OTS Canada set-up compared to the DRDC Valcartier's tests with a partial detonation or explosion (Type II or III) with the 0.39mm (0.0155") confinement and a detonation (Type I) with 1.14mm (0.045") confinement as opposed to an explosion reaction. The results being very similar for IMX-104 and PAX-48 with a burning reaction (Type V), only pictures of the latter one are presented in Figure 8 for the two thicknesses of confinement. The confinement and sample casing were open by pressure but remained in large pieces. Furthermore, as shown in the

pictures, a lot of unreacted explosive was visible on the recovered set-ups.

Table III – Variable Confinement Cook-Off Test (VCCT) results – Intermediate heating rate

Formulation	0.39mm (0.0155") confinement		1.14mm (0.045") confinement	
	Reaction T°	Reaction type	Reaction T°	Reaction type
IMX-104 (OSX-7)	182°C (360°F)	V	179°C (354°F)	V
PAX-48 (OSX-8)	189°C (372°F)	V	190°C (374°F)	V
Composition B	182°C (360°F)	II - III	183°C (361°F)	I



0.39 mm (0.0155")	1.14mm (0.045")	0.39 mm (0.0155")	1.14mm (0.045")
Composition B		PAX-48 (OSX-8)	

Figure 8 - VCCT results – Intermediate heating rate

The tests with the fast heating rate are still on-going at the time of the writing of this paper but we expect to present them at the symposium.

4. SUMMARY AND FUTURE WORK

Studies on the properties of two IM melt-pour dinitroanisole (DNAN) based formulations, IMX-104 and PAX-48 previously known as OSX-7 and OSX-8, were performed by GD-OTS Canada in order to provide additional data to complete previously obtained data on the processing properties, projectiles filling, mechanical and physical properties presented in a previous paper.

The computer simulations using Cheetah 5.0 thermochemical code provided very good approximation (within 3%) of the experimental values of detonation velocities and pressures of these formulations so this tool can be considered adequate to compute the detonation properties for this type of formulations.

The detonations velocities of the IMX-104 and PAX-48 are about 90% of the composition B values and the detonation pressures are about 80% of the composition B values as shown both experimentally and from computations. The Gurney coefficient of these formulations obtained from computations is about 90% of the composition B value.

Bullet impact tests conducted with 0.5 cal APM2 bullet on bare 105mm M1 projectiles led to Type V reactions for both IMX-104 and PAX-48 compared to Type I for the composition B filled projectile used as the baseline.

Intermediate heating rate results (25°C/hr (45°F/hr)) from variable confinement cook-off test (VCCT) performed with 0.39mm (0.0155") and 1.14mm (0.045") confinements produced respectively an explosion/partial detonation and a detonation for composition B. A burning

reaction was obtained for both IMX-104 and PAX-48 at both confinement thicknesses.

Additional studies including cylinder tests, physical properties during ageing, large scale gap tests (LSGT), additional insensitive munitions tests as well as filling of other types of projectiles and additional VCCT tests are planned to further increase our knowledge of these explosive formulations. It is also planned to test other formulations of this type such as OSX-12.

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