QUALIFICATION TESTING OF THE INSENSITIVE TNT REPLACEMENT EXPLOSIVE IMX-101

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ABSTRACT

The Program Manager for Combat Ammunition Systems at PEO Ammunition and the US Army ARDEC at Picatinny Arsenal had a requirement to implement Insensitive Munitions (IM) technology in a 155mm artillery round. The overall PM CAS objective was to reduce the hazard classification of the 155mm round from HC 1.1 and implement an IM solution while maintaining or exceeding warhead performance. With support from OSD, Office of Technology Transition (TTI) and the Joint Insensitive Munitions Technology Program (JIMTP), the insensitive TNT replacement explosive IMX-101 recently completed characterization testing for energetic material qualification in preparation for projectile Final Type Qualification in the 155mm artillery round. IMX-101 was fully characterized for hazard and performance behavior in accordance with the DoD Energetics Qualification Program Matrix for main charge explosives. Over 17,000 kg of IMX-101 had been produced at BAE-Holston from which one batch had been selected for qualification. The characterization data for IMX-101 demonstrated that the explosive was extremely insensitive to all stimuli including impact, friction, ESD, thermal, and sympathetic detonation. Set-back sensitivity was less than TNT and Comp B. The variation of properties with age was minimal. Critical temperature determination indicated that IMX-101 had an acceptable margin of handling safety for explosive production and warhead loading. Importantly, IMX-101 demonstrated detonation velocity results equivalent to TNT and 155mm artillery round arena testing indicated excellent warhead fragmentation. A series of 155mm artillery rounds filled with IMX-101 were tested per the IM certification standards according to MIL-STD-2105C and compared to TNT filled rounds. The IM results with IMX-101 demonstrated dramatic improvement with passing reactions for Sympathetic Detonation, Shaped Charged Jet Impact, Fast Cook-off, and Slow Cook-off while mild reactions were obtained for Bullet and Fragment Impact tests.

INTRODUCTION

The Program Manager for Combat Ammunition Systems at PEO Ammunition and the US Army ARDEC at Picatinny Arsenal had a requirement to implement Insensitive Munitions (IM) technology in a 155mm artillery round by way of an Engineering Change Proposal (ECP). The IM 155mm artillery round ECP was a joint Army/USMC program. The overall objective was to reduce the hazard classification of the explosive fill from 1.1 and implement a system IM solution while maintaining or exceeding warhead performance. The new insensitive explosive fill, IMX-101, was developed to replace the sensitive TNT explosive currently used in 155mm artillery rounds. With the support of OSD-TTI, The Joint Insensitive Munitions Technology Program (JIMTP), PEO AMMO, USMC, and PM CAS, IMX-101 was generated at production scale quantities and articles were cast for testing. This paper summarizes the process and results for the full qualification characterization of IMX-101 according to the DoD Energetics Qualification Program Matrix for main charge explosives.[1] The DoD Energetic Materials Qualification Process is designed to assess the safety and suitability of an explosive for general use by employing standardized test methods and protocols recognized by each North Atlantic Treaty Organization (NATO) country. The qualification characterization of IMX-101 presented here demonstrated that the explosive was extremely insensitive to all stimuli including slow cookoff and sympathetic detonation. Importantly, IMX-101 demonstrated detonation velocity results equivalent to TNT at the same cast density. Critical temperature determination indicated that IMX-101 had an acceptable margin of handling safety for explosive production and warhead loading.

IMX-101 had excellent response to aging conditioning and demonstrated no change in impact, friction, ESD, thermal, and sympathetic detonation properties. In addition, IMX-101 and its ingredients were found to be less toxic than RDX and the IMX-101 detonation products were calculated to be benign. Subsequent life-cycle environmental and safety analysis beyond the scope of this study indicated that the IMX-101 waste stream was known and manageable.

All high explosive loaded 155mm unitary warhead projectiles have a Hazard Classification (HC) of 1.1 due to the sensitivity of the TNT or Comp B explosive fill and do not meet Insensitive Munition (IM) requirements for cook-off, bullet and fragment impact, sympathetic detonation, and shaped charge jet response.[2] The 1.1 hazard classification of the legacy explosive fills required that large quantity-distance criteria were imposed for bulk storage of 155mm ammunition thereby reducing the efficiency of the logistics supply chain (e.g., the separation distance required for 4500-kg of 1.1 explosive was 381-m).[3] The implementation of a lower hazard class such as HC 1.6 would reduce the quantity-distance requirement for 4500-kg explosive to 52-m allowing for a more efficient use of storage space and a reduction of the logistics burden. In an effort to obtain the HC 1.6 for IMX-101, an Extremely Insensitive Detonating Substance (EIDS) assessment was initiated where IMX-101 readily passed EIDS Cap, EIDS Gap, and Susan impact testing. Finally, an important feature of less sensitive explosive fills is that system IM requirements become more achievable. The ultimate IM objectives for the 155mm artillery round are as follows: (1) Demonstrate Type III response for Sympathetic Detonation (SD) without barriers at the 155mm diameter, (2) Demonstrate Type V response for Fast Cookoff (FCO) of the artillery round, (3) Demonstrate Type III/V response for Shaped Charge Jet (SCJ) at TNT fill energy, (4) achieve the above mentioned IM goals and maintain system performance (e.g., Gurney energy and blast overpressure), (5) achieve the IM goals and maintain acceptable production and life cycle costs for an affordable and producible round within the existing industrial base, and (6) characterize Slow Cookoff (SCO), Bullet Impact (BI), and Fragment Impact (FI) and obtain passing response. A series of 155mm artillery rounds filled with IMX-101 were tested according to MIL-STD-2105C. IM test results demonstrated dramatic improvement over the TNT baseline with passing reactions in Sympathetic Reaction, Shaped Charged Jet Impact, Fast and Slow Cook-off tests and mild reactions in the Bullet and Fragment Impact tests. The IM test results in the 155mm artillery round filled with IMX-101 will be presented in a subsequent paper.

RESULTS AND DISCUSSION

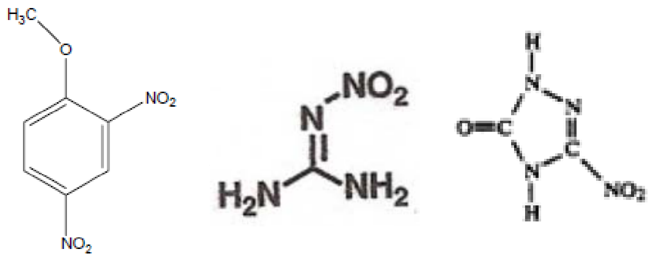
EXPLOSIVE QUALIFICATION DATA

The IMX-101 explosive was formulated from the inexpensive and available ingredients DNAN, NQ, and NTO as shown in Table I. Nuclear Magnetic Resonance (NMR) analysis of the ingredients contained in the IMX-101 formulation can be found in Figure 1. The detonation attributes were measured to be equivalent to TNT with less hazard sensitivity as explained below. IMX-101 is a melt pour explosive and is manufactured and processed like TNT. Over 17,000 kg (37,000 lbs) of IMX-101 was produced in this phase with a typical batch size of 545 kg (1200 lb). One batch (Lot#BAE07K375-007) was characterized for the explosive qualification. Following explosive qualification, additional 107,000 lbs was produced at BAE-Holston Army Ammunition Plant.

The DoD Energetic Materials Qualification Process is designed to provide a comprehensive assessment of the safety and suitability of an explosive for an intended role by employing standardized test methods and protocols recognized by each NATO country. The data summarized below includes mandatory tests and data requirements as specified by AOP-7 in addition to other explosive characterization tests required by the DoD Energetic Materials Qualification Board (EMQB). The final test protocols were coordinated with the Navy Ordnance Safety and Security Activity (NOSSA). The RDX reference standard was Type II, Class 5 and the TNT reference standard was general purpose.

Table I. The IMX-101 Ingredients and Formulation Compared to TNT and Comp B

	IMX-101	TNT	Comp B
2,4-Dinitroanisole (DNAN)	43.5 (±2)	--	--
Nitroguanidine (NQ)	36.8 (±2)	--	--
3-Nitro-1,2,4-triazol-5-one (NTO)	19.7 (±2)	--	--
Trinitrotoluene (TNT)	--	100	40
RDX	--	--	60



DNAN NQ NTO

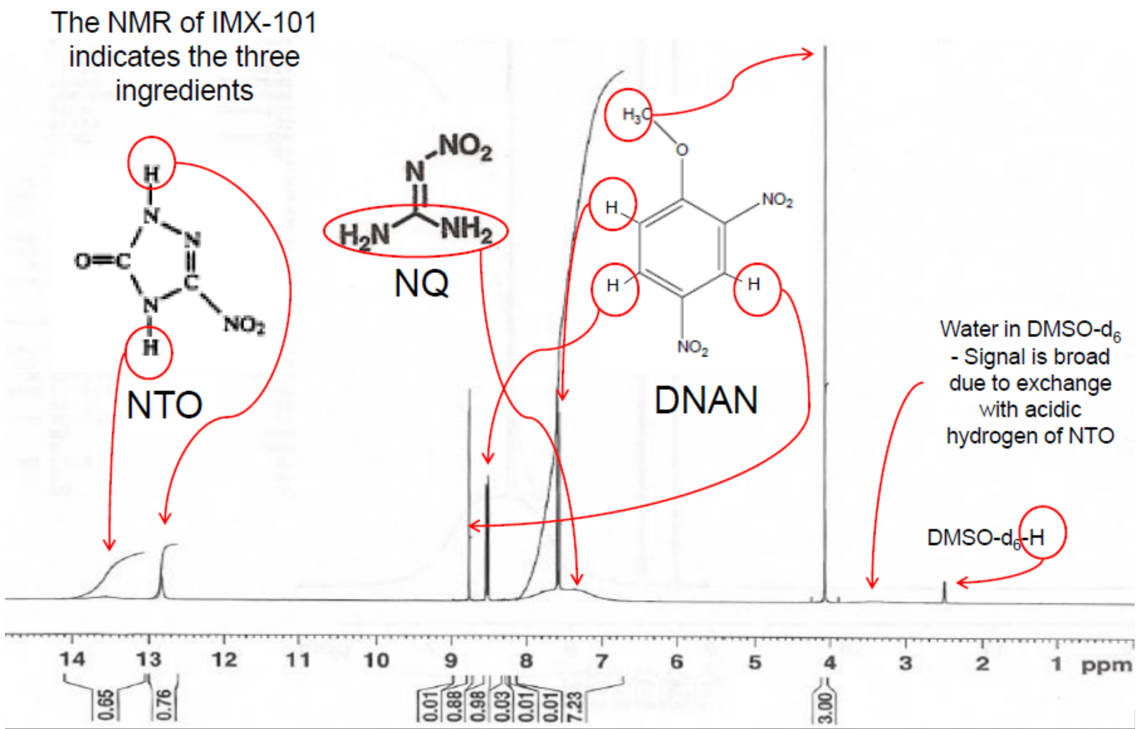


Figure 1. Nuclear Magnetic Resonance (NMR) analysis of IMX-101.

THERMAL CHARACTERIZATION

The VTS was performed according to AOP-7, US 202.01.001 (formerly MIL-STD-1751A (1061 or 1063)) or STANAG 4556 where 5.0 g IMX-101 was subjected to 100 °C for 48 hr or 100 °C for 40 hr and the quantity of gas evolved was measured (Table II). The criterion is ≤ 2 ml/g gas evolved. IMX-101 produced 0.50 ml/g at 100 °C for 48 hr and 0.34 ml/g at 100 °C for 40 hr. By comparison, RDX produced 0.12 ml/g at 100 °C for 48 hr and TNT produced 0.10 ml/g at 100 °C for 48 hr. IMX-101 was thermally stable under those conditions. Compatibility of IMX-101 with contact materials in the 155mm artillery round was also conducted by the VTS method where the materials were combined with IMX-101 at a ratio of 1.0. The results are not shown in Table II as no incompatibilities were observed.

Thermal Stability at +75 °C was performed according to AOP-7, US 202.01.013 (TB 700-2, UN Test 3c) where 50 g IMX-101 was subjected to 75 °C for 48 hr and the sample was observed for evidence of self heating and measured for weight loss. The criterion is failure due to explosion, burning, or decomposition. IMX-101 did not react. By comparison, RDX and TNT did not react. IMX-101 was thermally stable under those conditions.

Differential Scanning Calorimetry (DSC) was performed according to AOP-7, US 202.01.020 (MIL-STD-1751A (1072)) or STANAG 4515 where 20 mg IMX-101 was subjected to a heating rate of 10 °C/min until decomposition of the sample occurred. The sample endotherm(s), exotherm(s), onset temperature(s), and peak temperature(s) were recorded (Table II). IMX-101 displayed no unusual thermal activity.

The Woods Metal Bath 5-second ignition temperature was performed according to AOP-7, US 202.01.016 (MIL-STD-650 (515.1)) where 1 g IMX-101 was subjected to a range of temperatures near its decomposition temperature. Time to explosion temperatures were recorded and the ignition temperature was reported for ignition at 5 seconds. There is no pass/fail criterion. The 5 second explosion temperature for IMX-101 was 262 °C. By comparison, RDX had a 5 second explosion temperature at 227 - 252 °C and TNT had a 5 second explosion temperature at 327 °C.

The isothermal Henkin Time to Explosion (TTE) test was performed according to AOP-7, US 202.01.012, section 5.5 (and reference k) where 40 mg IMX-101 was subjected to a range of temperatures near its decomposition temperature. Times to explosion and explosion temperatures were recorded. The criterion was no explosion in 1000 seconds (2000 seconds in 4 consecutive tests – AFRL). The Henkin TTE for IMX-101 was 218 °C (ARL) and 209 °C (AFRL). By comparison, RDX had a Henkin TTE at 215 °C and TNT had a Henkin TTE at 286 °C.

The Critical Temperature Calculation (Tc) was performed according to AOP-7, US 202.01.012 (MIL-STD-1751A (1074)) where kinetic data was obtained from variable heating rate DSC. The Tc was derived from the Frank-Kamenetskii (F-K) equation (eq 1), 1-liter cookoff geometry, and an iterative process. The criterion is Tc > 82 °C at any size and the time to explosion at 82 °C exceeds 500 days. For the 1-liter spherical geometry, the Tc for IMX-101 was 105 °C (ARDEC), 107 °C (ARL), and 112 °C (BAE). By comparison, RDX had a Tc at 149 °C and TNT had a Tc at 160 °C. Because the IMX-101 Tc was calculated by this method to be 105 °C, the same as the processing temperature, the 1-liter spherical cookoff test was performed to verify the accuracy of the prediction (see 1-liter Spherical Cookoff Test below).

$$Tc = E_a/R\ln(A^2\rho QZE_a/Tc^2\lambda\delta R) \qquad (1)$$

Where:
Tc = critical temperature (ºK)
Ea = Arrhenius activation energy (cal mol^{-1})
Z = pre-exponential (s^{-1})
A = a dimension (e.g., radius of a sphere)
Q = heat of the self-heating reaction (not detonation or combustion)(cal g^{-1})
δ = shape factor (e.g., 3.32 for spheres)
R = gas constant (1.987 cal mol^{-1} $ºK^{-1}$)
ρ = density (g $(cm^3)^{-1}$)
λ = thermal conductivity (cal cm^{-1} s^{-1} $ºC^{-1}$)

Table II. Small-Scale Thermal Qualification Data for IMX-101

TEST TITLE	TEST METHOD	TEST CONDITION	TEST RANGE OR LIMIT	TEST RESULT	REFERENCE RESULT
Vacuum Thermal Stability (VTS)	AOP-7, US 202.01.001	5.00±0.05g 100 °C/48 h Or 100 °C or 120 °C /40 h	≤ 2 ml/g of gas evolved	0.50 ml/g (100 °C/48 h) 0.34 ml/g (100 °C/40 h)	RDX: 0.12 TNT: 0.10 ml/g
Thermal Stability at +75 °C	AOP-7, US 202.01.013	50g 75 °C/48 h	Evidence of Self Heating and/or Weight Loss	No Reaction	RDX: No Reaction TNT: No Reaction
DSC	AOP-7, US 202.01.020	20 mg 10 °C/min	Endotherm(s): Exotherm(s): Onset Temps Peak Temps	Endotherm: 95 °C Exotherm: Onset: 212 °C Peak: 223 °C	RDX: Endotherm: 205 °C Exotherm: Onset: 210 °C Peak: 241 °C TNT: Endotherm: 77 °C Peak: 300 °C
Woods Metal Bath (5-sec explo temp)	AOP-7, US 202.01.016	1 g Temperatures near Decomposition	Time to Explosion Temperatures over range 0.5-s to 9.0-s	262 °C	RDX: 227-252 °C TNT: 327 °C
Henkin Time to Explosion	AOP-7, US 202.01.012, section 5.5 (and reference k)	40 mg Temperatures near Decomposition	Time to Explosion (t_e) and Explosion Temperature (T_e)	ARL: 218 °C USAF: 209 °C 4 NO GO at 2000 sec	RDX: 215 °C TNT: 286 °C
Critical Temperature Calculation (Tc)	AOP-7, US 202.01.012	Kinetic Data obtained from variable heating rate DSC. Experimental Tc from 4.3 results	Tc > 82 °C at any size. Time to explosion at 82 °C exceeds 500 days	Tc: 1-liter geometry ARDEC: 105 °C ARL: 107 °C BAE: 112 °C BAE ARC: 151 °C	RDX: 149 °C TNT: 160 °C Comp B = 136 °C

The 1-liter spherical cookoff test Tc was performed according to AOP-7, US 202.01.021 (MIL-STD-1751A (1075)) where kinetic data was obtained from variable heating (3.3 °C/hr) of a 1-liter round bottom flask filled with the test explosive. The Tc was derived from the Frank-Kamenetskii (F-K) equation (eq 1), 1-liter cookoff geometry, and an iterative process. There is no pass/fail criterion. For the 1-liter spherical geometry, the Tc for IMX-101 was 145 °C (ARDEC), 145 °C (ARL), and 139 °C (AFRL). By comparison, RDX had a Tc at 154 °C and TNT had a Tc at 211 °C. The 1-liter data demonstrated that the DSC derived Tc was too conservative. To validate the 1-liter result, a 12-liter cookoff test was performed with IMX-101. The 12-liter Tc for IMX-101 was 148 °C validating the 1-liter result and demonstrating that the Tc effect does not scale versus test vessel diameter (Figure 2). The minimum margin of safety for processing a melt pour explosive is Tc ≥ 30 °C above the desired processing temperature.[4] The processing temperature of IMX-101 is 105 °C giving a margin of safety of > 35 °C.

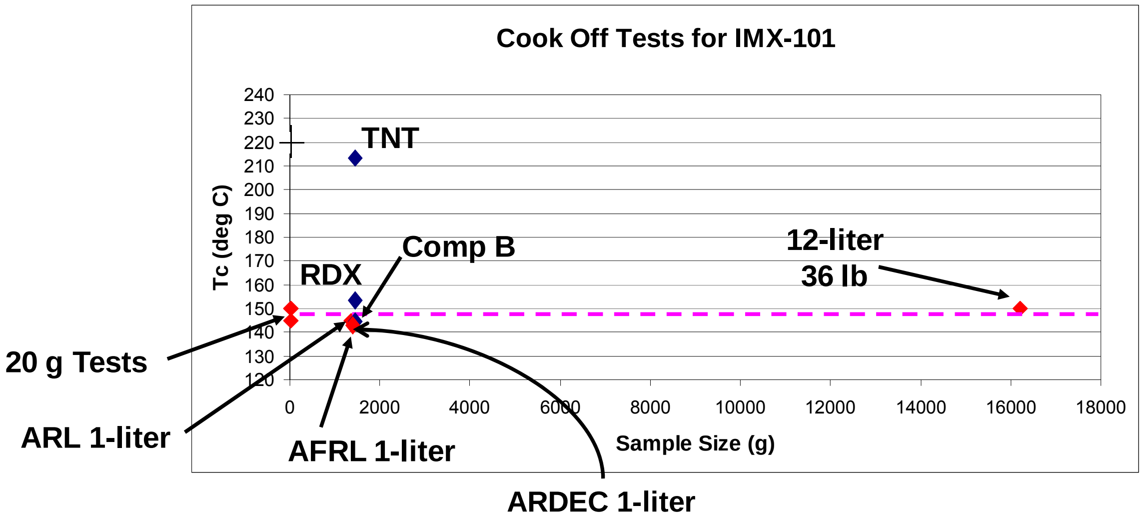


Figure 2. The IMX-101 1-liter critical temperature verification and absence of scaling.

The variable confinement cookoff test (FCO & SCO) was performed according to STANAG 4491 (also AOP-7, US 202.01.002) where approximately 50 g IMX-101 (per test) was subjected to a heating rate of 10 °C/s for FCO and a heating rate of 3.3 °C/hr for SCO over a range of confinement until a deflagration transition was obtained. IMX-101 exhibited a Burn reaction in FCO over a confinement range of 0.4 mm to 1.5 mm at which point the testing was ended. IMX-101 exhibited a Burn reaction in SCO over a confinement range of 0.4 mm to 0.8 mm and a Pressure Rupture over a confinement range of 1.1 mm to 1.5 mm at which point the testing was ended. By comparison, Comp A5 (98.5% RDX) exhibited a detonation in FCO at 0.4 mm confinement and a partial detonation in SCO at 0.4 mm confinement. Thus, IMX-101 was far less violent in cookoff than a desensitized RDX formulation.

The small-scale burn test was performed according to TB 700-2, UN Test 3d (also AOP-7, US 202.01.014) where two 10 g and two 100 g trials were subjected to a burning bed of sawdust and kerosene. The criterion is failure due to explosion or detonation. IMX-101 did not explode or detonate. By comparison, TNT did not explode or detonate. RDX was not tested. The small-scale burn test is required for hazard classification but is not a mandatory qualification test.

Table II. Small-Scale Thermal Qualification Data for IMX-101 (cont.)

TEST TITLE	TEST METHOD	TEST CONDITION	TEST RANGE OR LIMIT	TEST RESULT	REFERENCE RESULT
1-liter Spherical Cook Off Test	AOP-7, US 202.01.021	Sample is heated from melt point at 3.3 °C/hr until decomposition	Minimum margin of safety for processing is Tc ≥ 30 °C above desired processing temperature	Tc: ARL: 145 °C USAF: 139 °C	RDX = 154 °C TNT = 211 °C Comp B = 143 °C IMX-101 at 12-liter; Tc = 148 °C
Variable Confinement (FCO & SCO)	STANAG 4491	50 g FCO = ~10 °C/s SCO = 3.3 °C/hr	Burn to Deflagration Transition	**FCO** T15: Burn T30: Burn T45: Burn T60: Burn **SCO** T15: Burn T30: Burn T45: Pres Rupture T60: Pres Rupture	Comp A5 (98.5% RDX); **FCO** T15 = detonation **SCO** T15 = partial detonation
Small-Scale Burn Test	TB 700-2 UN Test 3d	Two 10 g and Two 100 g trials	Explosion = Failure	No Explosion Pass	RDX: TNT: Pass

Table III. Small-Scale ESD, Impact, and Friction Results for IMX-101

TEST TITLE	TEST METHOD	TEST CONDITION	TEST RANGE OR LIMIT	TEST RESULT	REFERENCE RESULT
Small-Scale ESD Test	AOP-7, US 201.03.001	30 mg "No Go" 20 trials 0.25 J	Not more sensitive than Comp B (ρ = 1.65 g/cc)	No Go	RDX: Go @ 0.25 J TNT: No Go @ 0.25 J
ERL/Bruceton Impact	AOP-7, US 201.01.001	35 mg 2.5 kg drop weight 50% Point	Not more sensitive than Comp B (ρ = 1.65 g/cc)	> 100 cm	RDX: 18 cm TNT: 88 cm
BAM Friction	AOP-7, US 201.02.006	Sample Config = 10 mm^3 "No Go" six trials 80 N Min	Not more sensitive than Comp B (ρ = 1.65 g/cc)	240 N	RDX: 168 N TNT: 216 N Comp B : 112N

OTHER SENSITIVITY CHARACTERIZATION

The Electrostatic Discharge (ESD) test was performed according to AOP-7, US 201.03.001 (MIL-STD-1751A (1032)) or STANAG 4490 where 30 mg IMX-101 was subjected to 0.25 J energy. IMX-101 exhibited no reaction in 20 trials at 0.25 J (Table III). By comparison, RDX did react at 0.25 J. TNT did not react at 0.25 J. IMX-101 was not reactive to electrostatic discharge.

The Explosive Research Laboratory (ERL) Impact, Bruceton Apparatus was performed according to AOP-7, US 201.01.001 (MIL-STD-1751A (1012)) where 35 mg IMX-101 was subjected to impact by a 2.5 kg drop weight from various heights. IMX-101 exhibited no reaction at 100 cm drop height at which point the test was ended. By comparison, RDX had a 50% point drop height of 18 cm. TNT had a 50% point drop height at 88 cm. IMX-101 was far less impact sensitive than either of the references.

The Bundesanstalt Für Materialprufung (BAM) friction test was performed according to AOP-7, US 201.02.006 (MIL-STD-1751A (1024)) where 50 mg IMX-101 was subjected to sliding friction over a range of pressure. IMX-101 exhibited no reaction at 240 N pressure. By comparison, RDX had no reaction at 168 N pressure. TNT had no reaction at 216 N pressure. IMX-101 was less friction sensitive than either of the references.

Shock sensitivity was attempted by NOL Large-Scale Gap Test (LSGT). The LSGT test was performed according to AOP-7, US 201.04.002 (MIL-STD-1751A (1041)) with unreliable results. The IMX-101 critical diameter was later determined to be 64 mm to 68 mm that was greater than the diameter of the LSGT pipe. The LSGT data was not reported. The Expanded Large-Scale Gap Test (ELSGT) is conducted when the explosive critical diameter is greater than the diameter of the LSGT confinement tube. The ELSGT was performed according to AOP-7, US 201.04.001 (MIL-STD-1751A (1043)) where a series of 73 mm diameter and 280 mm long samples were subjected to a calibrated shock and the 50% gap thickness was determined (Table IV). The criterion is that the new explosive is not more sensitive than Comp B. IMX-101 had a 50% gap thickness of 158 cards (59 kbar). By comparison, Comp B had a 50% gap thickness of 489 cards (10 kbar). TNT had 50% gap thickness of 457 cards (14 kbar). IMX-101 was far less shock sensitive than either of the references.

The base gap set back sensitivity test was performed according to ARDEC test protocol.[5a] A set of 20 g samples that were 13 mm ID and 95 mm long were held in a test fixture that simulated a base gap over a range of gaps up to 4.4 mm. The fixture was launched in a tube simulating a 15,000 g launch acceleration. IMX-101 exhibited no reaction in 5 trials at the maximum gap of 4.4 mm (Table IV). Thus, the 50% point for reaction of IMX-101 in the base gap test was greater than 4.4 mm at 15,000 g's. By comparison, TNT had a 50% point base gap of 2.7 mm and Comp B had a 50% point base gap of 2.1 mm.

The simulated cavity collapse test was performed according to Navy protocol.[5b] The pressure loading was up to 10x for the 5"/54 gun. No reaction was obtained for hemispherical cavities up to 13 mm in diameter and/or random porosity. The explosivity of dust test was performed according to ASTM Method E1515-98 where a dust cloud of IMX-101 was generated in a 20 liter chamber followed by attempted ignition. The Minimum Explosible Concentration (MEC) was calculated from a plot of the change in chamber pressure versus dust concentration. The MEC is the lowest concentration of dust for which the pressure ratio (PR) $\geq$ 2. The MEC for IMX-101 was 800 to 900 g/m^3. By comparison, the MEC for RDX was 300 to 400 g/m^3. The MEC for TNT was 100 to 200 g/m^3. The MEC for IMX-101 was far greater than either of the references.

The irreversible growth test was performed according to AOP-7, US 202.01.011 (MIL-STD-1751A (1162)) where three 25 mm diameter x 25 mm long pellets were subjected to 30 cycles over the temperature range -54 °C to +71 °C. The advisory criterion is not more than 1.0% growth. IMX-101 exhibited 8% growth. By comparison, TNT exhibits greater than 3% growth and Comp B exhibits greater than 8.5% growth. RDX was not tested. The growth exhibited by IMX-101 is typical of melt pour explosives.

Table IV. Other Sensitivity Results for IMX-101

TEST TITLE	TEST METHOD	TEST CONDITION	TEST RANGE OR LIMIT	TEST RESULT	REFERENCE RESULT
Expanded Large-Scale Gap Test (ELSGT)	AOP-7, US 201.04.001	Sample Config = 73 mm (ID) x 280 mm (L) 50% Point	Not more sensitive than Comp B (ρ = 1.65 g/cc)	158 cards, 59 kbar ρ = 1.64 g/cc	Comp B: 489 cards, 10 kbar, ρ = 1.69 g/cc TNT: 457 cards, 14 kbar, ρ = 1.59 g/cc
Set-Back Sensitivity	Local Protocol ARDEC Test Method[5a]	20 g Sample Config = 13 mm (ID) x 95 mm (L)	Pass = “no go” to 95% confidence level	15,000 G Gap = 4.4-mm No Reaction Pass	15,000 G TNT Gap = 2.7-mm Comp B Gap = 2.1-mm
Explosivity of Dust	ASTM Method E1515-98	Powder ≥ 95% minus 200 mesh	Lowest concentration of dust for which the pressure ratio (PR) ≥ 2 is the MEC	800-900 g/m^3	RDX: 300 to 400 g/m^3 TNT: 100 to 200 g/m^3
Growth	AOP-7, US 202.01.011	Sample Config = 25 mm (D) x 25 mm (L). 30 cycles at -54 °C (-65 °F) and 71 °C (+160 °F).	≤ 1.0 %	8%	TNT: 3% (over temp range 21 °C to °60 C) Comp B: +8.5% PBX-9502: 1.5 – 3.2%
Exudation	AOP-7, US 202.01.010	Sample Config = 25 mm (D) x 125 mm (L). 71 °C (+160 °F) for 320 hr.	≤ 0.1%	0.05%	TNT: 0.673%

It should be noted that the irreversible growth of TNT is used as a process aid to improve the quality of the cast article and improve TNT adhesion to the shell. A typical TNT growth profile is shown in Figure 3.[6] In addition, a series of 155-mm artillery rounds loaded with IMX-101 were subjected to the temperature and humidity conditioning shown in Figure 4. All temperature cycled rounds launched without incident and functioned as expected.

The exudation characteristics test was performed according to AOP-7, US 202.01.010 (MIL-STD-1751A (1161)) where three 25 mm diameter x 125 mm long pellets were subjected to +71 °C for 320 hr followed by loss in weight analysis. The advisory criterion is not more than 0.1% exudates. IMX-101 exhibited 0.05% loss in weight. By comparison, TNT exhibited 0.67% loss in weight. RDX was not tested. The loss in weight exhibited by IMX-101 was far less than for TNT.

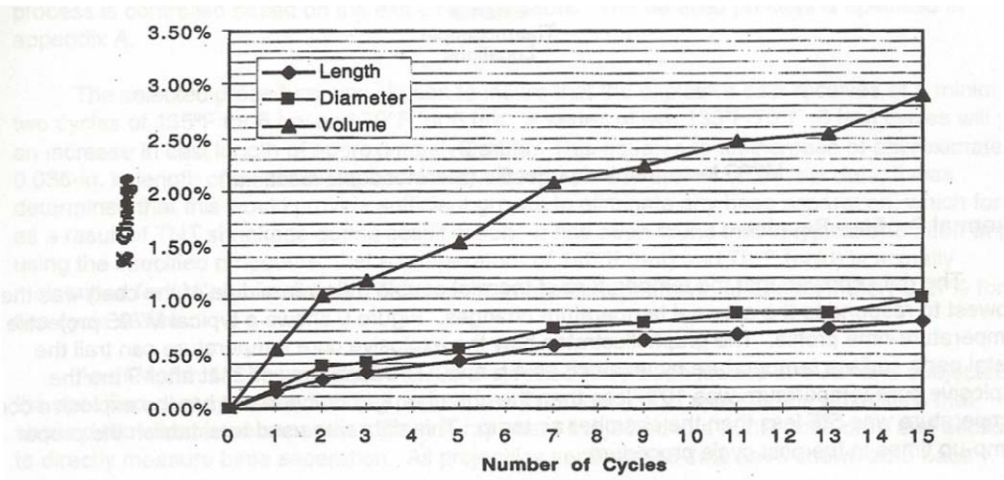


Figure 3. The growth profile of TNT over the temperature range +21 °C to +60 °C.

Number of Rounds	Temperature Condition (°C)	Humidity Condition (%RH)	Number of Days	Number of Cycles	Gun Pressure Condition	Result
30	**33 to 71**	**80 - 14**	**7**	**7**	**Max Service**	**All Pass**
30	**-51**		**7**		**Max Service**	**All Pass**
60	**33 to 71**	**80 - 14**	**28**	**28**	**Max Service**	**All Pass**
60	**-51**		**14**		**Max Service**	**All Pass**
16	**30 to 60**	**95**	**10**	**10**	**Max Service**	**All Pass**
16	**30**	**95**	**28**		**Max Service**	**All Pass**
1	**75**		**2**		**Max Service**	**Pass**

Figure 4. The temperature and humidity conditioning of a series of 155-mm artillery rounds that were later launched and functioned.

VARIATION OF PROPERTIES WITH AGE

The aging characteristics of IMX-101 was performed according to AOP-7, Edition 2, Rev. 3, Chapter 8, Table 4, USA (Navy) (NAVSEAINST 8020.5C). Table V shows the compositional analysis comparison between the time zero sample, the 70 °C at 6 months sample, and the 60 °C at 8 months sample. The DNAN concentration does not change, there is a slight decrease of NQ, and a slight increase of NTO. Even though there was a small compositional change between the time zero sample and 60 °C sample, the aged sample remained with specification (See Table I). The following was conducted according to protocol: (1) samples were aged at 60 °C in sealed containers and sampled at 1 ,2 ,4 ,6 , and 8 months (Table VI), (2) samples were aged at 70 °C in sealed containers and sampled at 1 ,2 ,4 , and 6 months (Table VII), and (3) samples were aged at 25 °C and 30% RH and sampled at 12 months (Table VIII). The aged samples were compared to time zero samples previously tested as above. There is no pass/fail criterion. However, the aged samples were compared to the un-aged time zero results for IMX-101. Any significant deviation of the aged samples from the un-aged sample was noted.

The IMX-101 samples aged at 60 °C exhibited only a slight decrease of the exotherm onset indicating no change of the thermal decomposition temperature for the aged sample. The impact, friction, and ESD results were unchanged from the un-aged. The friction series did indicate an anomaly that was attributed to operator error. The ELSGT did not change significantly.

The IMX-101 samples aged at 70 °C exhibited only a slight decrease of the exotherm onset indicating no change of the thermal decomposition temperature for the aged sample. The impact, friction, and ESD results were unchanged from the un-aged. The friction series did indicate an anomaly that was attributed to operator error. The ELSGT did not change significantly.

The IMX-101 samples aged at 25 °C and 30% RH exhibited only a slight decrease of the exotherm onset indicating no change of the thermal decomposition temperature for the aged sample. The impact, friction, and ESD results were unchanged from the un-aged. The ELSGT did not change significantly.

Finally, additional optional testing included the cube cracking test (NAVSEAINST 8020.5C) where 152 mm diameter billets (L/D = 1) were subjected to 30 days and 60 days at 60 °C and then examined for fissures. IMX-101 billets exhibited no change as assessed from X-ray analysis.

Table V. Aged Compositional Analysis

Month	Temperature (°C)	DNAN (%)	NQ (%)	NTO (%)
0	NA	43.5	36.8	19.7
6	70	43.1	36.6	19.1
8	60	43.5	35.4	20.6

Table VI. IMX-101 Aged 60 °C in Sealed Container

Month	DSC	ERL Impact	BAM Friction	ESD	ELSGT
0	Endotherm: 95 °C Exotherm: Onset: 212 °C Peak: 223 °C	> 100 cm	168 N	No Go @ 0.25 J	158 cards, 59 kbar ρ = 1.64 g/cc
1	Exotherm: Onset: 202 °C	> 100 cm	96 N	No Go @ 0.25 J	
2	Exotherm: Onset: 201 °C	> 100 cm	96 N	No Go @ 0.25 J	
4	Exotherm: Onset: 204 °C	> 100 cm	160 N	No Go @ 0.25 J	150 cards, 61 kbar ρ = 1.65 g/cc
6	Exotherm: Onset: 202 °C	> 100 cm	160 N	No Go @ 0.25 J	
8	Exotherm: Onset: 196 °C	> 100 cm	168 N	No Go @ 0.25 J	148 cards, 61 kbar ρ = 1.65 g/cc

Table VII. IMX-101 Aged 70 °C in Sealed Container

Month	DSC	ERL Impact	BAM Friction	ESD	ELSGT
0	Endotherm: 95 °C Exotherm: Onset: 212 °C Peak: 223 °C	> 100 cm	168 N	No Go @ 0.25 J	158 cards, 59 kbar ρ = 1.64 g/cc
1	Exotherm: Onset: 207 °C	> 100 cm	108 N	No Go @ 0.25 J	
2	Exotherm: Onset: 206 °C	> 100 cm	108 N	No Go @ 0.25 J	
3	Exotherm: Onset: 201 °C	> 100 cm	108 N	No Go @ 0.25 J	166 cards, 58 kbar ρ = 1.65 g/cc
4	Exotherm: Onset: 198 °C	> 100 cm	160 N	No Go @ 0.25 J	
6	Exotherm: Onset: 200 °C	> 100 cm	160 N	No Go @ 0.25 J	174 cards, 56 kbar ρ = 1.65 g/cc

Table VIII. IMX-101 Aged 25 °C and 30% RH

Month	DSC	ERL Impact	BAM Friction	ESD	ELSGT
0	Endotherm: 95 °C Exotherm: Onset: 212 °C Peak: 223 °C	> 100 cm	168 N	No Go @ 0.25 J	158 cards, 59 kbar ρ = 1.64 g/cc
12	Endotherm: °C Exotherm: Onset: 203 °C Peak: 211 °C	> 100 cm	216 N	No Go @ 0.25 J	135 cards, 64 kbar ρ = 1.65 g/cc

SUMMARY AND CONCLUSIONS

The Insensitive Munitions Explosive IMX-101 was formulated and developed to replace TNT in a 155mm artillery round. Following initial hazard, performance, and 155mm artillery round IM testing, IMX-101 was generated in production quantities and fully characterized for safety and suitability according to the DoD Energetics Qualification Program Matrix for main charge explosives. Small-scale hazard testing demonstrated that IMX-101 was not more sensitive than TNT. Critical temperature assessment indicated that IMX-101 was safe to process in large batches and typical melt-pour processing conditions. Small-scale cookoff showed that IMX-101 did not detonate during decomposition under confinement. The shock sensitivity of IMX-101 was far less than TNT and Comp B. IMX-101 demonstrated no setback sensitivity. IMX-101 did exhibit irreversible growth but the growth was easily managed in a confined warhead and no loss of performance or increase in hazard has been attributed to this property. The variation of properties with age for IMX-101 flake and cast articles indicated no aging issues. The formal IMX-101 qualification certification was issued by the US National Service Authority in January 2010.

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REFERENCES

1. See: DoD Energetics Qualification Program for Main Charge Explosives and instructions in: (a) “Manual of Data Requirements and Tests for the Qualification of Explosive Materials for Military Use”, AOP-7, 2nd ed. Rev. 3; NATO; December 2007. (b) “Principles and Methodology for the Qualification of Explosive Materials for Military Use”, STANAG 4170, 3rd ed., NATO, 2007. (c) “DoD Energetics Qualification Program Matrix for Main Charge Explosives”, OUSD(AT&L), May 2003. (d) Department of Defense Ammunition and Explosives Hazard Classification Procedures, TB700-2, June 2005. (e) Safety and Performance Tests for the Qualification of Explosives (High Explosives, Propellants, and Pyrotechnics), MIL-STD-1751A, December 2001.
2. Department of Defense Acquisition Manager's Handbook for Insensitive Munitions, Rev. 1, January 2004.
3. DOD Ammunition and Explosives Safety Standards, DOD 6055.9-STD, July 1999.
4. McKenney, R.L. and Krawietz, T.R., “One-Liter Test: A Mid-Scale Safety Characterization Test For Melt-Castable Explosives”, AFRL-MN-EG-TR-1999-7049 (July 1999).
5. (a) For base gap setback sensitivity; Barry Fishburn, ARDEC, Private Communication. (b) For setback simulator testing; H. W. Sandusky, G. P. Chambers, and V. J. Carlson, “Setback Simulation of Fielded and Candidate Explosive Fills for 5”/54 Guns,” Proceedings of 1998 JANNAF Propulsion Systems Hazards Subcommittee Meeting, CPIA Publ. 681, Vol. II, Dec 1998, pp. 137-145.
6. “Post Cycle Temperature Conditioning for the 155-mm Projectile”, ARWEC-TR-98011, December 1998.