FFI-rapport 2015/02184

Intermediate scale gap test of MCX-6002

Gunnar Ove Nevstad

FFI Forsvarets forskningsinstitutt

FFI-rapport 2015/02184

Intermediate scale gap test of MCX-6002

Gunnar Ove Nevstad

Norwegian Defence Research Establishment (FFI)

18 November 2015

FFI-rapport 2015/02184

120503

P: ISBN 978-82-464-2746-1
E: ISBN 978-82-464-2747-8

Keywords

Testing

Sprengstoffer

Approved by

Ivar Sollien Research Manager

Jon E. Skjervold Director

English summary

The main explosive filling in munitions must have properties that fulfill the IM-requirements in STANAG 4439. An important property for several of the IM threats is the shock sensitivity of the explosive filling. With that background, a Chemring composition MCX-6002 containing NTO/TNT/RDX (51/34/15) have been tested for shock sensitivity in Intermediate Scale Gap Test according to STANAG 4488 Ed 2. MCX-6002 is a melt-cast composition. The density difference between melted and solid material is significant, resulting in challenges to obtain high quality of the fillings. Tested gap test tubes had an average filling density of 95.7 + 1.5 % of theoretical maximum density. X-ray of the tubes showed good filling homogeneity in the bottom of the tube. The areas of low density, containing pores and voids, were concentrated in the upper part of the tubes. During testing all tubes were therefore initiated from the bottom.

The obtained result of 40.5 kbar indicates that MCX-6002 has low shock sensitivity, and is a promising candidate as main filling for munitions to achieve the IM requirements.

Sammendrag

Hovedsprengstoff må ha egenskaper som tilfredsstiller kravene til IM (Insensitive Munitions) gitt i STANAG 4439. En viktig egenskap for å motstå flere av IM-truslene er sjokkfølsomheten til sprengstoffyllingen. Med denne bakgrunnen har Chemring-komposisjonen MCX-6002 med sammensetning NTO/TNT/RDX (51/34/15) vært testet for sjokkfølsomhet i Intermediate Scale Gap Test i henhold til STANAG 4488 Ed 2. MCX-6002 er en smelt-støp komposisjon. Forskjellen i tetthet mellom flytende og fast masse er stor, noe som gir utfordringer med å oppnå god kvalitet og tetthet på støpte fyllinger. For de testede gaptestrørene har sprengstoffyllingene i gjennomsnitt en tetthet på 95,7 + 1,5 % av teoretisk maksimum tetthet. Røntgen av rørene viser imidlertid en god homogenitet for nedre halvdel av fyllingene og at områder med lav tetthet, porer og tomrom er konsentrert i den øvre delen av rørene. Av den grunn ble rørene initiert fra bunn.

Resultat for MCX-6002 med en 50 % sannsynlighet for initiering var 40.5 kbar. Dette er en svært lav sjokkfølsomhet, og viser at MCX-6002 er en komposisjon med stort potensial for å oppnå gode IM-egenskaper for ammunisjon hvor den benyttes som sprengstoffylling.

Contents

Abbreviations

BAMO	3,3-Bis-azidomethyl oxetane
DNAN	2,4-dinitroanisole
GA	Glycidyl azide
GA/BAMO	Glycidyl azide- (3,3-bis(azidomethyl)oxetane) Copolymers
HMX	Octogen/1,3,5,7-tetranitro-1,3,5,7-tetraazacyclooctane
HWC	Hexogen/Wax/Graphite (94.5/4.5/1)
IM	Insensitive Munitions
IMX-104	NTO/DNAN/RDX (53/31.7/15.3) (3)
MCX	Melt Cast Explosive
MCX-6100	NTO/DNAN/RDX (53/32/15)
NTO	3-Nitro-1,2,4 Triazol 5-one
RDX	hexogen/1,3,5 -trinitro-1,3,5-triazacyclohexane
TMD	Theoretical Maximum Density
TNT	2,4,6-trinitrotoluene
WP	Work Package

1 Introduction

Under the EDA project arrangement No B-0585-GEM2-GC “Formulation and Production of New Energetic Materials” different melt cast compositions in addition to compositions containing GA/BAMO polymers have been studied. Norway’s main activity in the project is synthesis of GA/BAMO polymers suitable for coating nitramines, used for production of press granules, press filling of munitions units or production of pressed charges.

Norway is the only country that uses the energetic binder for explosive charges. Italy and Germany use their polymers as binders in propellants. The compositions that we produced have a high content of HMX (94-97%). Their primary application will be as boosters or main fillings for shaped charges.

To broaden the number of 40 mmm shell compositions in the generic fragmentation testing (WP 4000), Norway included 4 melt-cast compositions. These are of interest for Norway as main fillers preferentially for large caliber munitions. Two of the compositions have TNT and two have DNAN as binder, while the fillers are NTO/RDX or NTO/HMX. These compositions have, in addition to fragmentation performance, been characterized for the most important properties as detonation velocity, detonation pressure and critical diameter.

This report presents results from our study of compositions, MCX-6002 with regard to shock sensitivity. MCX-6002 contains TNT as binder and the filler is NTO/RDX. Nominal content is 34/51/15 (TNT/NTO/RDX). This composition has NTO/RDX content in the same range as the DNAN based US composition IMX-104 (1) and the Chemring MCX-6100 composition (2).

The shock sensitivity has been determined by use of the Intermediate Scale Gap Test described in STANAG 4488 (3). The shock sensitivity of a composition is important from two different viewpoints. First, in order to be able to design a reliable initiation train it’s necessary to know the pressure needed for initiation. On the other hand, the shock sensitivity will be one of the most important properties of an explosive filling, to be able to protect the munitions against external impact. The responses from threats as Bullet Impact, Fragment Impact, Sympathetic Detonation and Shaped Charge Jet depend upon shock properties of the acceptor. The IM requirements given in STANAG 4439 (4) are easier achieved with main explosive fillings with low shock sensitivity.

Theoretical performance of MCX-6002 has been calculated with Cheetah 2.0 (5). For comparisons of the performance compositions as TNT, Comp B and Octol 60/40 have been included in these calculations.

2 Experimentally

2.1 Filling of gap test tubes

The filling of the test tubes was done by Chemring Nobel at Sætre. The tube was placed in a Teflon holder with an alumina sheet covering the bottom end of the tube. At the top of the tube an extension of 2-3 cm was placed in order to get enough filling mass of the tube as the filling goes from liquid to solid during the cooling process. After the composition melting and heating to 100-102 ^{o}C it was filled into the tube in an incubator at the same temperature over the night. After the filling of the composition into the tube, the tube was moved to the incubator for 2 hours. The solidification/cooling process of the casted items took place at room temperature.

Figure 2.1 The figure shows the top of tubes No1 to No 5.

Figure 2.2 The figure shows the bottom of tubes No 1 to No 5.

Figure 2.1 shows the top of tubes No 1 to No 5 after adjustment. Tube No 1 was not filled to the top, approximately 0.8 cm of the filling was missed. Figure 2.2 shows the bottom of tubes No 1 to No 5 after the alumina foil was removed and the filling level adjusted.

Figure 2.3 The figure shows the top of tubes No 6 to No 10.

Figure 2.4 The figure shows the bottom of tubes No 6 to No 10.

Figure 2.3 and 2.4 shows top and bottom of tubes No 6 to No 10 after cleaning and adjusting of filling level.

2.2 X-ray

All tubes were X-rayed with a 320 kV apparatus at Nammo Raufoss. All tubes were X-rayed at 0^o and 90^o to determine if observed defects were in the centre of the tubes or not. X-ray pictures of all tubes as reproduced in Figures 2.5- 2.7.

Figure 2.5 X-ray picture of tubes No 1 to No 7 at 0^o.

From Figure 2.5 it can be seen that there are areas in the upper part of the tubes with low density. The lower density areas are much darker than the rest of the charge. For tube No 2 it seemed to be an empty space of 2-3 cm from the top. The X-ray pictures explain the moderate density obtained for the fillings (see Table 3.1).

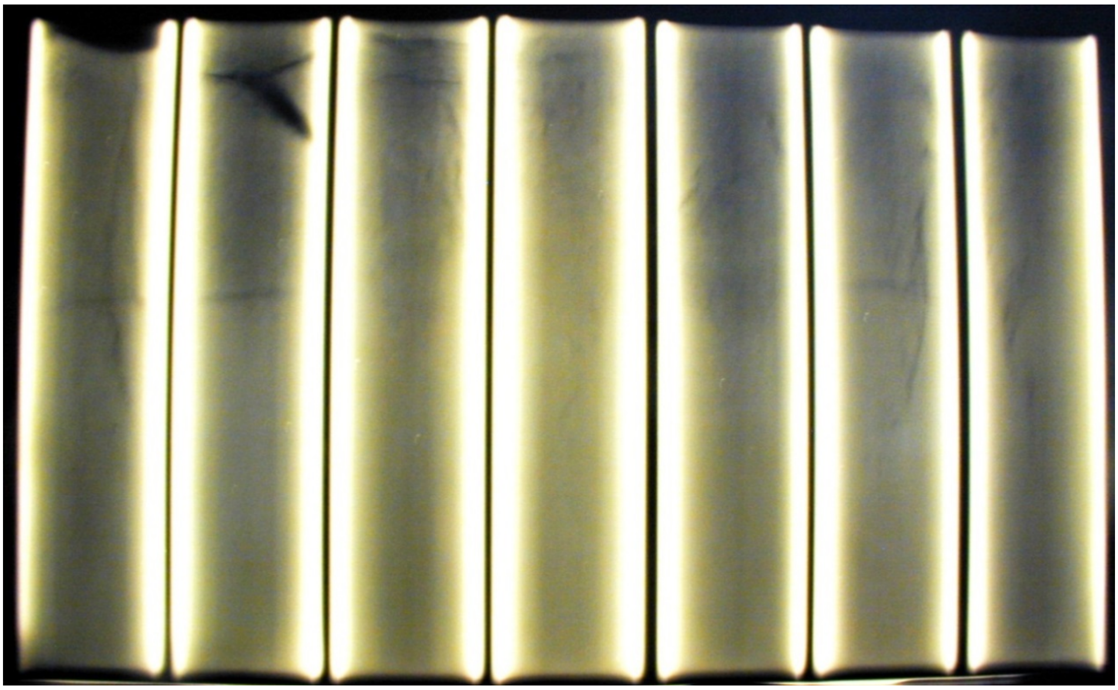

Figure 2.6 X-ray picture of tubes No1 to No 7 after being turned 90^o.

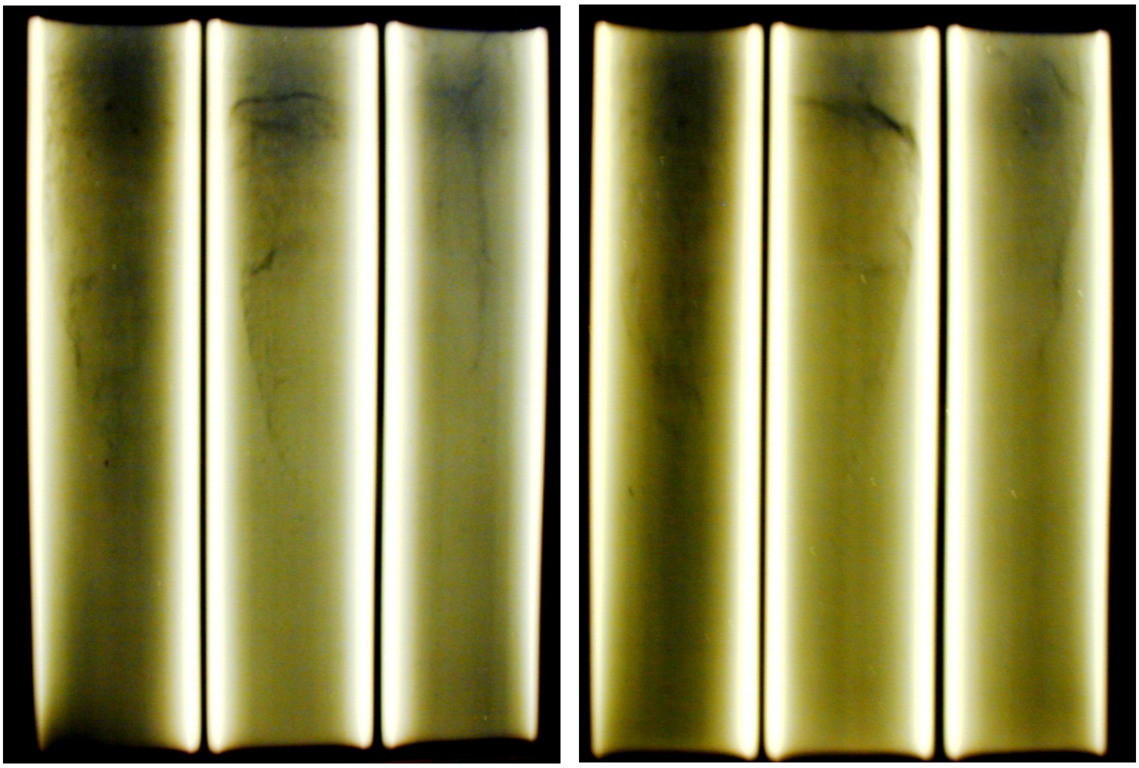

Figure 2.7 X-ray pictures of tubes No 8 to No 10; left picture at 0°; right picture after the tubes were turned 90 °.

Figure 2.7 shows X-ray pictures of tubes No 8 to No 10 from 0° and 90° angels. And as for the tubes No 1 to No 7, all tubes had several dark areas with low density in the upper part of the filling. Tube No 9 had probably in addition an empty space.

However, all tubes had few defects in the lower 10 cm of the filling and they were decided to be fired. The firings were done by initiation from the bottom. Having the bottom of the tubes closest to the donor got more reproducible results.

2.3 Intermediate Scale Gap Test

We have used the Intermediate Scale Gap Test described in STANAG 4488 (3) for determination of the shock sensitivity with one exception. The used cards had a thickness of 0.254 mm instead of 0.19+0.002/-0.001 mm recommended in the STANAG.

As booster explosive we used HWC containing RDX/Wax/Graphite (94.5/4.5/1). The booster was pressed with 7.2 tons pressure and a dwell time of 60 seconds. The control report for the booster explosive is given in Appendix A. Initiation was done with a detonator No 8.

Figure 2.8 shows the test conditions for the firings.

Figure 2.8 The picture shows the test setup used for firing of the Intermediate Scale Gap Test.

2.4 Theoretical calculations

Theoretical calculations have been done with Cheetah 2.0 (5). The results are summarized in section 3.4, and summary print outs for each calculation are given in Appendix B.

3 Results

3.1 Filling quality

All tested tubes were washed before filling, followed by measurement of volume and weight. After filling the tubes were cleaned for spilled explosive during the filling. The filling level both at the bottom and top were adjusted to give a plan surface, see Figure 2.1-2.4. After these operations the filled tubes were weighed and the weight of the fillings calculated. Table 3.1 gives all measured properties in addition to the calculated density of the fillings. The low density of the filling in tube No 1 is explained by the filling height. For tube No 2 the X-ray pictures explain the low density.

Tube No	Weight (g)	Inner diameter		Average Inner Radius (mm)	Height (mm)	Volume (cm^3)	Weight Tube + Filling (g)	Weight of Filling (g)	Density (g/cm^3)
		Top (mm)	Bottom (mm)						
1	881.10	39.58	39.60	19.795	200.09	246.31	1290.68	409.58	1.663
2	884.91	39.59	39.58	19.793	200.39	246.62	1296.91	412.00	1.671
3	880.04	39.63	39.66	19.823	200.39	247.37	1305.34	425.30	1.719
4	914.70	39.20	39.34	19.635	201.05	243.51	1336.20	421.50	1.731
5	875.52	39.62	39.70	19.830	200.10	247.20	1296.64	421.12	1.704
6	898.77	39.52	39.46	19.745	199.90	244.84	1319.65	420.88	1.719
7	882.38	39.59	39.57	19.790	200.15	246.26	1307.63	425.25	1.727
8	876.84	39.70	39.67	19.843	200.16	247.58	1303.81	426.97	1.725
9	904.73	39.28	39.30	19.645	200.04	242.53	1328.03	423.30	1.745
10	905.60	39.32	39.32	19.660	200.61	243.60	1335.47	429.87	1.765
Average density for filling of tube No 2 to No 10									**1.723±0.026**

*Not fully filled (7-10 mm was not filled)

Table 3. 1 Properties of the tested tubes filled with MCX-6002 composition.

TMD for MCX-6002 is **ρ=1.7997 g/cm^3**. The average density of the fillings of 1.723±0.026 g/cm^3 for tubes No 2 to No 10 is equivalent to 95.7±1.5 %TMD. This gives a moderate filling quality.

3.2 Firing of gap tubes

The first tube to be tested was tube No 1 with a barrier thickness of 135 cards between donor and acceptor. Initiation was from the bottom. Figure 3.1 shows the test item before firing and the witness plate and recovered rests of the tube after firing. The response was no reaction. All explosive was consumed and the tube was fragmented into large fragments.

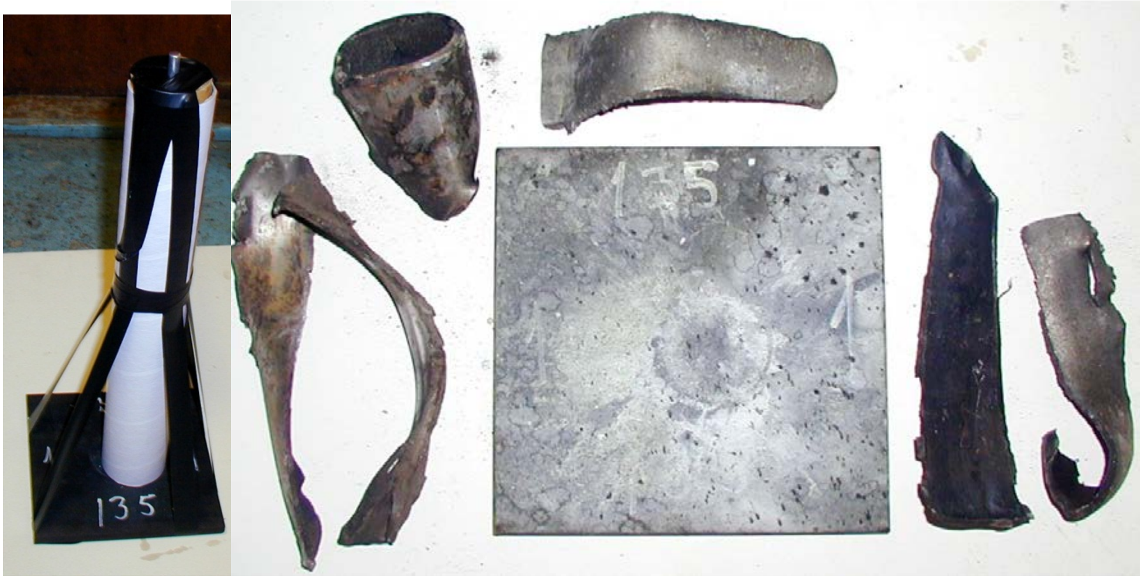

Figure 3.1 Pictures of tube No 1 before and after firing. Barrier thickness: 135 cards. Response: No reaction.

Firing No 2 was with tube No 2. The barrier thickness between the donor and acceptor was reduced to 125 cards. Figure 3.2 shows the test item before firing and the witness plate after firing. The witness plate got a hole indicating full detonation response.

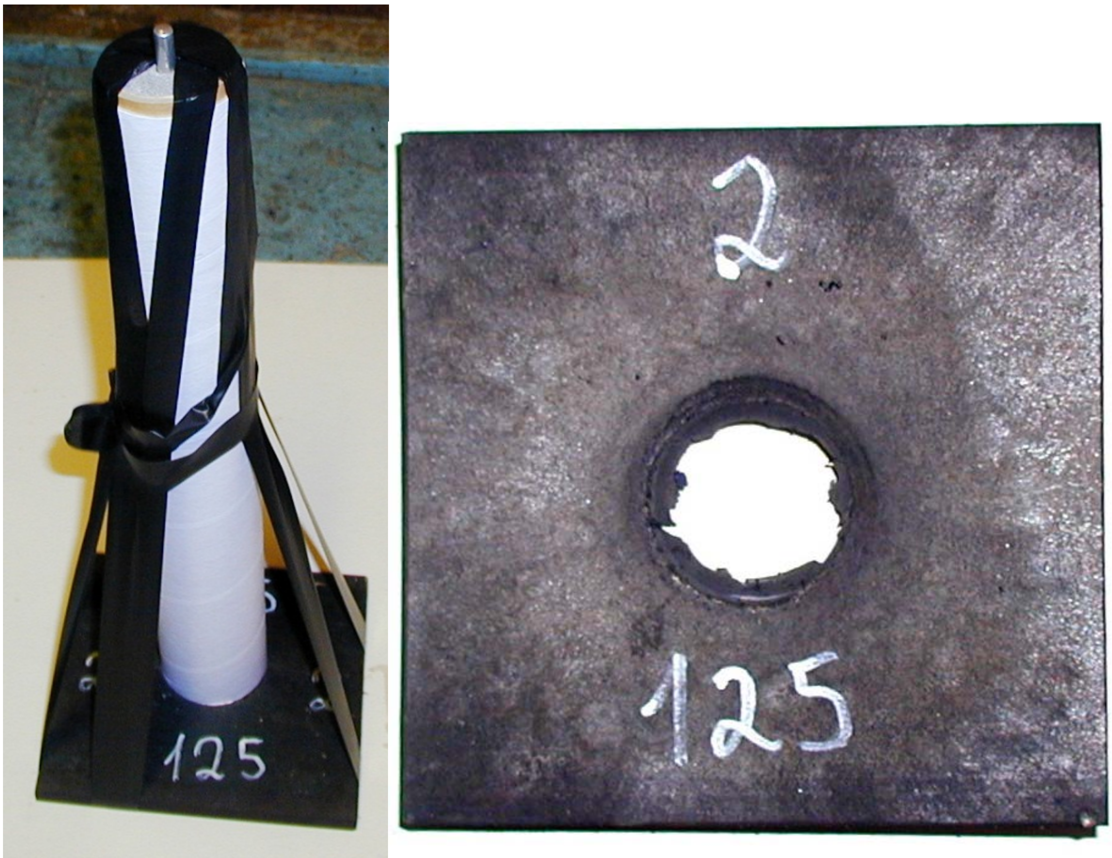

Figure 3.2 Pictures of tube No 2 before and after firing. Barrier thickness: 125 cards. Response: Detonation.

Firing No 3 was with tube No 3. The barrier thickness between the donor and acceptor was increased to 130 cards. Figure 3.3 shows the test item before firing and the witness plate and the recovered rests of the tube after firing. The witness plate is undamaged and the sizes of the tube fragments indicate the response as no reaction.

Figure 3.3 Pictures of the tube No 3 before and after firing. Barrier thickness: 130 cards. Response: No reaction.

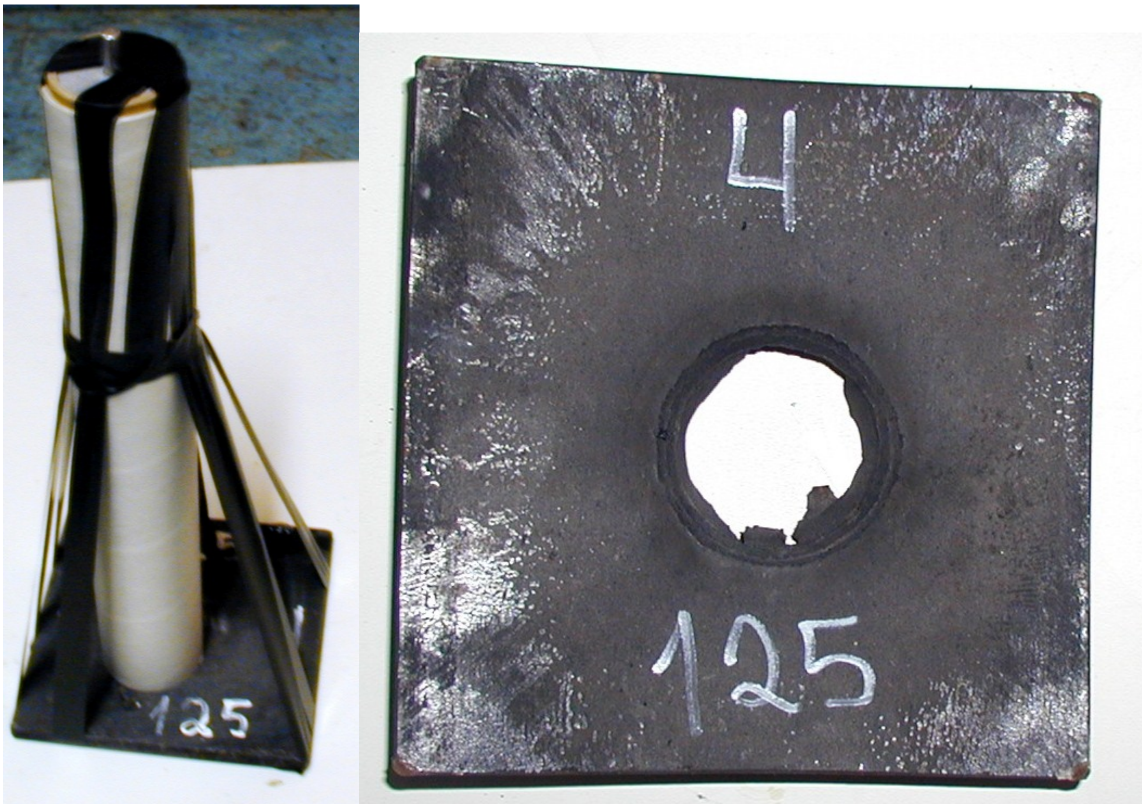

Figure 3.4 Pictures of tube No 4 before and after firing. Barrier thickness: 125 cards. Response: Detonation.

Firing No 4 was with tube No 4. The barrier thickness between the donor and acceptor was reduced to 125 cards. Figure 3.4 shows the test item before firing and the witness plate after firing. The witness plate has a hole indicating a detonation response.

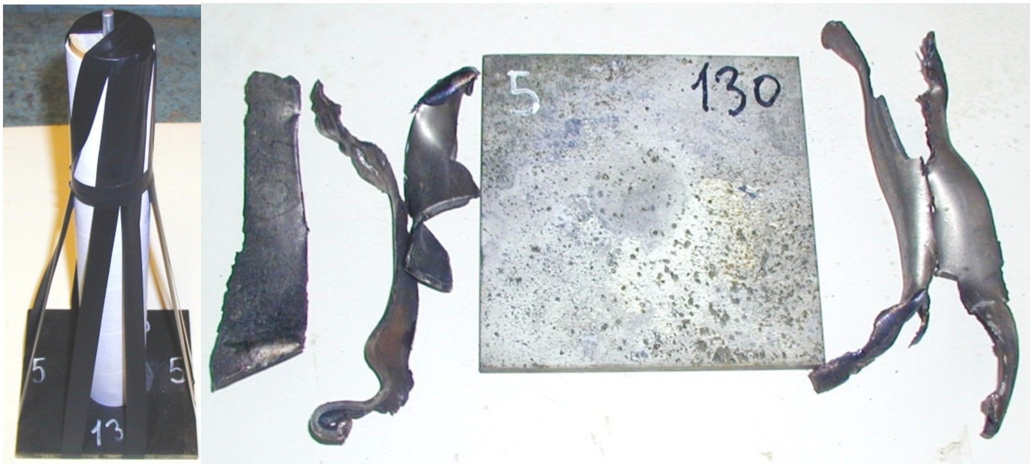

Figure 3.5 Pictures of tube No 5 before and after firing. Barrier thickness: 130 cards. Response: No reaction.

Firing No 5 was with tube No 5 with a barrier thickness between the donor and acceptor of 130 cards. Figure 3.5 shows the test item before firing, and the witness plate and the recovered tube fragments after firing. The witness plate is undamaged, and the sizes of the tube fragments both indicate that the response is no reaction.

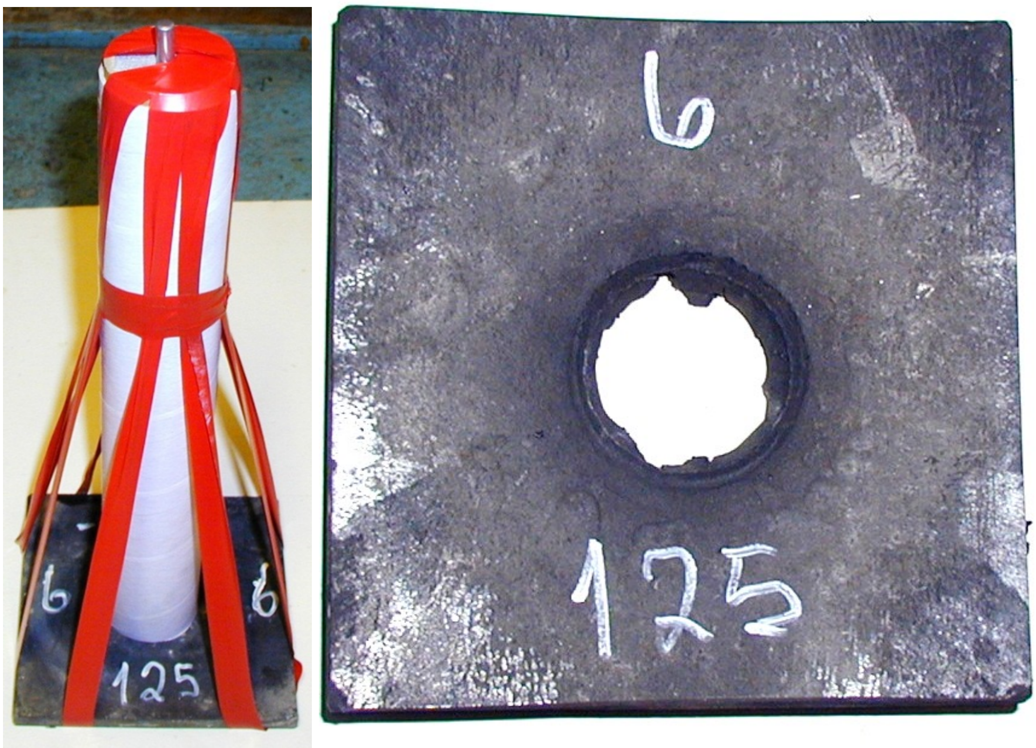

Figure 3.6 Pictures of tube No 6 before and after firing. Barrier thickness: 125 cards. Response: Detonation.

Firing No 6 was with tube No 6. The barrier thickness between the donor and acceptor was reduced to 125 cards. Figure 3.6 shows the test item before firing and the witness plate after firing. The witness plate got a hole indicating full detonation response.

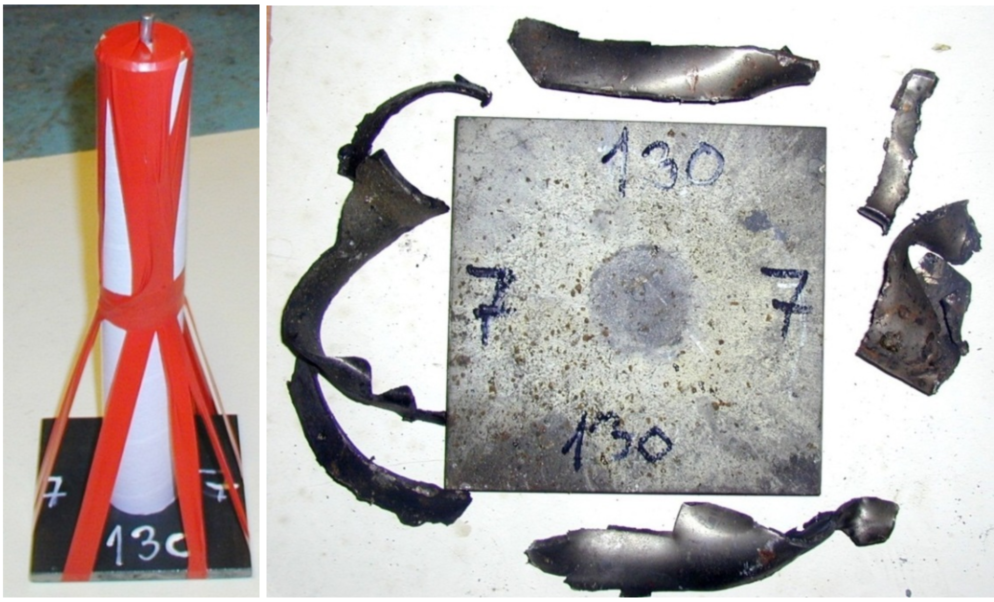

Figure 3.7 Pictures of tube No 7 before and after firing. Barrier thickness: 130 cards. Response: No reaction.

Firing No 7 was with tube No 7 with a barrier thickness between the donor and acceptor of 130 cards. Figure 3.7 shows the test item before firing, and the witness plate and the recovered tube fragments after firing. The witness plate is undamaged, and the sizes of the tube fragments indicate that the response is no reaction.

Figure 3.8 Pictures of tube No 8 before and after firing. Barrier thickness: 125 cards. Response: Detonation.

Firing No 8 was with tube No 8 The barrier thickness between the donor and acceptor was reduced to 125 cards. Figure 3.8 shows the test item before firing and the witness plate after firing. The witness plate got a hole indicating detonation response.

Figure 3.9 Pictures of tube No 9 before and after firing. Barrier thickness: 130 cards. Response: No reaction.

Firing No 9 was with tube No 9 with a barrier thickness between the donor and acceptor of 130 cards. Figure 3.9 shows the test item before firing and the witness plate after firing. The witness plate is undamaged giving no reaction response. The acceptor tube is fragmented into relatively large fragments.

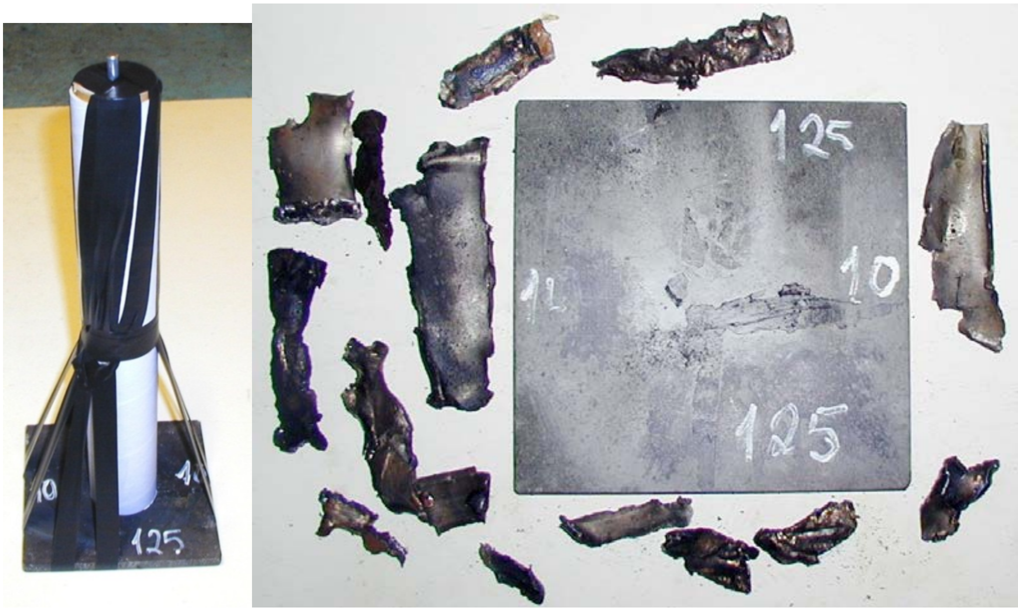

Figure 3.10 Pictures of tube No 10 before and after firing. Barrier thickness: 125 cards. Response: No reaction.

Firing No 10 was with tube No 10. The barrier thickness between the donor and acceptor was reduced to 125 cards. Figure 3.10 shows the test item before firing and the witness plate after firing. The witness plate is undamaged giving no reaction response. However, the reaction in the acceptor tube is more severe than in several of the other no reaction responses observed with barrier thickness of 130 cards. The number of fragments is higher and the size smaller than for the other tubes. The observations indicate that the response of the acceptor is close to a detonation.

3.3 Summary of the results

Table 3.2 gives a summary of conditions and responses for all firings with MCX-6002 filled tubes. In Figure 3.11 the same information is shown as a diagram.

Firing No	Tube No	Number of cards	Thickness (mm)	Response
1	1	135	34.29	No reaction
2	2	125	31.75	Detonation
3	3	130	33.02	No reaction
4	4	125	31.75	Detonation
5	5	130	33.02	No reaction
6	6	125	31.75	Detonation
7	7	130	33.02	No reaction
8	8	125	31.75	Detonation
9	9	130	33.02	No reaction
10	10	125	31.75	No reaction

Table 3.2 Summary of the responses for the tested GAP-tubes filled with MCX-6002 composition.

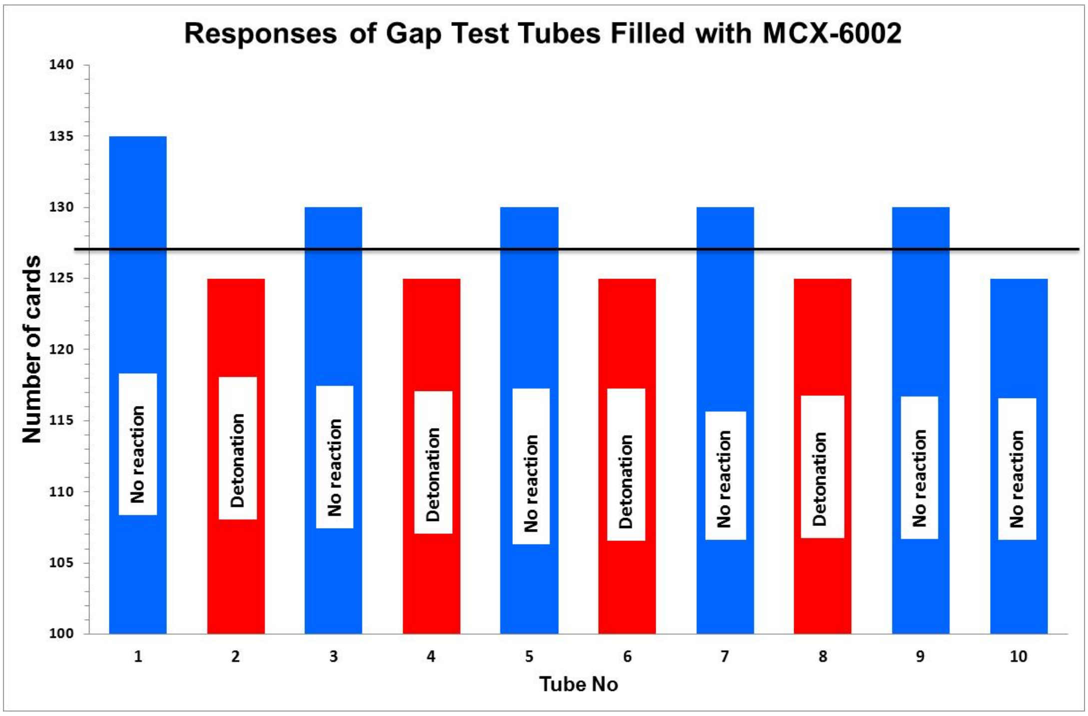

Figure 3.11 Responses for tested gap tubes filled with MCX-6002 composition.

As shown in Figure 3.11 the responses for equal barrier thickness is highly reproducible. After the first detonation with a barrier thickness of 125 cards, only one firing (firing No 10 with tube No 10) was not following the trend of no reaction response. 50% probability for detonation occurs with a barrier thickness of 127 cards or 32.3 mm. According to the table in Appendix C a 32.3 mm thick barrier corresponds to a pressure of **40.4 kbar.**

This result is significantly better than for Comp B and Octols. In (8) the shock sensitivity for Octol 60/40 was found to be 14.5 kbar and for Octol 70/30 16.0 kbar. In (6) the sensitivity for Comp B is determined to be (ρ=1.69) 210 cards (19 kbar). However, MCX-6002 is significantly more sensitive than MCX-6100, which in (2) was determined to be 58.5 kbar.

3.4 Cheetah calculations

The Table 3.3 gives Cheetah 2.0 calculated performance properties for MCX-6002 with both the BKWS and BKWC product library. For comparisons, the properties of TNT, Comp B and

Property	BKWS Product Database				BKWC Product Database			
	MCX-6002	TNT	COMP B	Octol 60/40	MCX-6002	TNT	COMP B	Octol 60/40
TMD (g/cc)	1.7997	1.6540	1.7207	1.7960	1.7997	1.6540	1.7207	1.7960
The C-J condition:								
Pressure (GPa)	26.83	20.75	27.39	30.21	27.22	19.57	26.90	30.16
Volume (cc/g)	0.428	0.460	0.443	0.426	0.423	0.454	0.436	0.418
Density (g/cc)	2.338	2.175	2.259	2.349	2.362	2.204	2.292	2.391
Energy (kJ/cc explosive)	3.6	2.49	3.26	3.56	3.24	2.44	3.35	3.75
Temperature (K)	3626	3715	3939	3948	3589	3711	3986	3998
Shock velocity (m/s)	8001	7236	8172	8454	7970	6886	7923	8214
Particle velocity (m/s)	1843	1734	1948	1990	1898	1719	1973	2045
Speed of sound (m/s)	6159	5502	6225	6464	6072	5167	5949	6169
Gamma	3.342	3.173	3.196	3.249	3.200	3.007	3.015	3.017
Freezing occurred at T = 1800 K and relative V =	1.888	2.363	2.273	2.225	1.828	2.399	2.305	2.236
Mechanical energy of detonation (kJ/cc)	-8.388	-7.871	-9.363	-9.904	-8.167	-7.526	-9.041	-9.584
Thermal energy of detonation	-0.000	-0.130	0.000	-0.000	-0.000	-0.101	0.000	-0.000
Total energy of detonation	-8.388	-8.001	-9.363	-9.904	-8.167	-7.627	-9.041	-9.584

Table 3.3 Calculated properties of MCX-6002 and other TNT melt-cast compositions.

Octol 60/40 is included. The results in Table 3.3 show that MCX-6002 has performance equal to Comp B and significantly better than TNT. Compared with Octol 60/40 the performance is slightly lower.

4 Summary

Shock sensitivity for MCX-6002 has been determined in Intermediate Scale Gap Test. The quality of the fillings in the tested tubes is lower than wanted. The X-ray investigation shows however, that at least half of the filling has an acceptable quality. Most defects and low density is concentrated in the upper half of the filling. By placing the bottom of the tube closest to the donor reproducible results have been obtained. The 50% point for detonation response has been determined to be 40.5 kbar.

References

1. Philip Samuels, Anthony Di Stasio, Leila Zunino, Daniel Zaloga, Charlie Patel, Sanjeev K Singh, Amy Chau: IM Results Comparison for DNAN for Based Explosives, IM Technology Gaps Workshop 20 to 24 June 2011, The Hague, The Netherlands.

2. Gunnar Ove Nevstad: Intermediate Scale Gap Test of MCX-6100, FFI-rapport 2015/02183, 18. November 2015.

3. STANAG 4439 JAIS (Edition 3) – Policy for introduction and assessment of Insensitive Munitions (IM), NSA/0337(2010)-JAIS/4439 17 March 2010.

4. STANAG 4488 JAIS (Edition 2) – Explosive, shock sensitivity tests, NSA/0448(2009)-JAIS/4488 27 April 2009.

5. Laurence E. Fried, W. Michael Howard, P. Clark Souers (August 20, 1998): Cheetah 2.0 User's Manual, UCRL_MA-117541 Rev. 5, Lawrence Livermore National Laboratory.

6. Leila Zunino, Philip Samuels, C Hu; IMX-104 Characterization for DoD Qualification, 2012 Insensitive Munitions& Energetic Materials Technology Symposium, Las Vegas, 14-17 May.

7. Philip Samuels, Leila Zunino, Keyur Patel, Brian Travers, Erik Wrobel, Henry Grau, Charlie Patel; Characterization of 2,4-Dinitroanisole (DNAN), 2012 Insensitive Munitions& Energetic Materials Technology Symposium, Las Vegas, 14-17 May.

8. Gunnar Ove Nevstad (2008): "Shock sensitivity testing of Octols", FFI-rapport 2008/00468.

Appendix A Control report HWC

KONTROLLRAPPORT B
etter EN 10204 - 3.1

Chemring Nobel

Kjøper/Mottaker FFI Postboks 25 2007 Kjeller	Bestillingsnummer V/ Gunnar Nevstad Bestillingsdato 16.01.14	Rapportnummer 045 Kontrolldato 27.01.14
Produsent Dyno Nobel ASA N-3476 Sætre NORWAY	Produksjonsdato 23.01.14	Offentlig oppdragsnummer
Lot nummer DDP14A0068-0002	Mengde 10 kg	
Sprengstofftype **RDX/VOKS/GRAFITT, 94,5/4,5/1**	Leveringsbetingelser/Teknisk underlag For testing	

Analyseresultater for loten

	Sammensetning			Fuktighet og flyktige bestanddeler	Surhet	
	RDX	Voks	Grafitt			
KRAV	94,5 ± 0,5 %	4,5 ± 0,5 %	1,0 ± 0,2 %	≤ 0,1%	≤ 0,02 %	
RESULTAT 03/14	94,4	4,7	0,9	0,0	0,00	0,0

	Uløste partikler på USS No. 60	Vacuum stabilitet	Volumvekt	Kornfordeling %, USS No.		
				> 12	> 18	< 100
KRAV	Ingen	≤ 1,2 ml/g	0,86 - 0,93g/ml	0	≤ 2	≤ 1
RESULTAT 03/14	ingen	0,1	0,89	0	0	1

Kjersti K Bernhoe (signature)
Kvalitetssjef

Chemring Nobel AS
High Energy Materials
Manager QA

Figure A. 1 Control report of the HWC used as donor explosive.

Appendix B Cheetah Calculations

B.1 BKWS product library

B.1.1 MCX-6002

```
Product library title: bkws library

Reactant library title: # Version 2.0 by P. Clark Souers


The composition:
Name       % wt.   % mol  % vol    Heat of      Mol.    TMD
                                  formation     wt.     (g/cc)
                                  (cal/mol)
nto        51.00   64.35  48.06    -24140    130.07     1.91 c2h2n4o3
tnt        34.00   24.57  37.00    -15057    227.13     1.65 c7h5n3o6
rdx        15.00   11.08  14.95     16496    222.13     1.81 c3h6n6o6

Density  =  1.7997 g/cc   Mixture TMD =  1.7997 g/cc   % TMD = 100.0000


The C-J condition:
The pressure           =          26.53 GPa
The volume             =          0.428 cc/g
The density            =          2.338 g/cc
The energy             =           3.06 kJ/cc explosive
The temperature        =           3626 K
The shock velocity     =          8.001 mm/us
The particle velocity =           1.843 mm/us
The speed of sound     =          6.159 mm/us
Gamma                  =          3.342


Cylinder runs:              % of standards
  V/V0      Energy    TATB      PETN      HMX     CL-20    TRITON
 (rel.)    (kJ/cc) 1.83g/cc 1.76g/cc 1.89g/cc 2.04g/cc 1.70g/cc
   1.00     -0.95
   2.20     -5.35      110        84        72        59       123
   4.10     -6.42      110        83        72        61       116
   6.50     -6.87      110        83        73        62       112
  10.00     -7.16      110        82        73        62       109
  20.00     -7.51      109        82        74        63       105
  40.00     -7.78      109        82        74        64       101
  80.00     -7.98      108        82        75        65        97
 160.00     -8.15

Freezing occurred at T =     1800.0 K and relative V =   1.888
The mechanical energy of detonation =      -8.388 kJ/cc
The thermal energy of detonation    =      -0.000 kJ/cc
The total energy of detonation      =      -8.388 kJ/cc

JWL Fit results:
E0   =       -8.693 kJ/cc
A    =      1008.11 GPa, B    =     9.16 GPa, C     =         1.32 GPa
R[1] =         5.00,     R[2] =     1.11,     omega =         0.37
RMS fitting error =   0.91 %
```

B.1.2 TNT

```
Product library title: bkws library
Reactant library title: # Version 2.0 by P. Clark Souers

The composition:
Name      % wt.   % mol  % vol    Heat of     Mol.   TMD
                                 formation    wt.    (g/cc)
                                 (cal/mol)
tnt       100.00 100.00 100.00   -15057   227.13     1.65 c7h5n3o6
Product library title: bkws library

Density  =  1.6540 g/cc   Mixture TMD =  1.6540 g/cc   % TMD = 100.0000


The C-J condition:
The pressure          =          20.75 GPa
The volume            =          0.460 cc/g
The density           =          2.175 g/cc
The energy            =           2.49 kJ/cc explosive
The temperature       =           3715 K
The shock velocity    =          7.236 mm/us
The particle velocity =          1.734 mm/us
The speed of sound    =          5.502 mm/us
Gamma                 =          3.173


Cylinder runs:             % of standards
  V/V0     Energy    TATB     PETN      HMX    CL-20   TRITON
 (rel.)   (kJ/cc)  1.83g/cc 1.76g/cc 1.89g/cc 2.04g/cc 1.70g/cc
   1.00    -0.78
   2.20    -4.49      93       71       60       50      103
   4.10    -5.50      95       71       62       52      100
   6.50    -5.95      96       72       63       53       97
  10.00    -6.26      96       72       64       55       95
  20.00    -6.64      97       73       65       56       93
  40.00    -6.94      97       73       66       57       90
  80.00    -7.18      97       74       67       58       87
 160.00    -7.39

Freezing occurred at T =     1800.0 K and relative V =   2.363
The mechanical energy of detonation =     -7.871 kJ/cc
The thermal energy of detonation    =     -0.130 kJ/cc
The total energy of detonation      =     -8.001 kJ/cc

JWL Fit results:
E0   =       -8.256 kJ/cc
A    =       681.39 GPa, B    =     7.56 GPa, C     =         1.20 GPa
R[1] =         4.91,     R[2] =     1.08,     omega =         0.30
RMS fitting error =   0.83 %
```

B.1.3 Comp B

Product library title: bkws library
Reactant library title: # Version 2.0 by P. Clark Souers

The composition:

Name	% wt.	% mol	% vol	Heat of formation (cal/mol)	Mol. wt.	TMD (g/cc)	
rdx	59.50	60.10	56.69	16496	222.13	1.81	c3h6n6o6
tnt	39.50	39.02	41.09	-15057	227.13	1.65	c7h5n3o6
paraffin	1.00	0.88	2.21	-128107	254.48	0.78	c18h38

Product library title: bkws library

Density = 1.7207 g/cc   Mixture TMD = 1.7207 g/cc   % TMD = 100.0000

The C-J condition:
The pressure = 27.39 GPa
The volume = 0.443 cc/g
The density = 2.259 g/cc
The energy = 3.26 kJ/cc explosive
The temperature = 3939 K
The shock velocity = 8.172 mm/us
The particle velocity = 1.948 mm/us
The speed of sound = 6.225 mm/us
Gamma = 3.196

Cylinder runs: % of standards

V/V0 (rel.)	Energy (kJ/cc)	TATB 1.83g/cc	PETN 1.76g/cc	HMX 1.89g/cc	CL-20 2.04g/cc	TRITON 1.70g/cc
1.00	-1.03					
2.20	-5.84	120	92	78	64	134
4.10	-7.07	122	92	80	67	128
6.50	-7.58	122	91	80	68	124
10.00	-7.92	121	91	81	69	121
20.00	-8.32	121	91	82	70	116
40.00	-8.62	121	91	82	71	112
80.00	-8.85	120	91	83	72	107
160.00	-9.04					

Freezing occurred at T = 1800.0 K and relative V = 2.273
The mechanical energy of detonation = -9.363 kJ/cc
The thermal energy of detonation = -0.000 kJ/cc
The total energy of detonation = -9.363 kJ/cc

JWL Fit results:
E0 = -9.661 kJ/cc
A = 907.61 GPa, B = 10.20 GPa, C = 1.52 GPa
R[1] = 4.91, R[2] = 1.10, omega = 0.37
RMS fitting error = 0.94 %

B.1.4 Octol 60/40

Product library title: bkws library

```
Reactant library title: # Version 2.0 by P. Clark Souers

The composition:
Name      % wt.   % mol  % vol    Heat of     Mol.   TMD
                                formation     wt.    (g/cc)
                                (cal/mol)
hmx        60.00  53.50  56.57    17866   296.17     1.91 c4h8n8o8
tnt        40.00  46.50  43.43   -15057   227.13     1.65 c7h5n3o6
Product library title: bkws library

Density  =  1.7960 g/cc   Mixture TMD =  1.7960 g/cc   % TMD = 100.0000


The C-J condition:
The pressure          =          30.21 GPa
The volume            =          0.426 cc/g
The density           =          2.349 g/cc
The energy            =           3.56 kJ/cc explosive
The temperature       =           3948 K
The shock velocity    =          8.454 mm/us
The particle velocity =          1.990 mm/us
The speed of sound    =          6.464 mm/us
Gamma                 =          3.249


Cylinder runs:             % of standards
  V/V0     Energy    TATB     PETN      HMX    CL-20   TRITON
 (rel.)   (kJ/cc)  1.83g/cc 1.76g/cc 1.89g/cc 2.04g/cc 1.70g/cc
   1.00    -1.12
   2.20    -6.31     130       99       84       70      145
   4.10    -7.59     131       98       86       72      138
   6.50    -8.12     130       98       86       73      133
  10.00    -8.46     130       97       87       74      129
  20.00    -8.87     129       97       87       75      124
  40.00    -9.17     128       97       88       75      119
  80.00    -9.41     128       96       88       76      114
 160.00    -9.60

Freezing occurred at T =     1800.0 K and relative V =   2.225
The mechanical energy of detonation =     -9.904 kJ/cc
The thermal energy of detonation    =     -0.000 kJ/cc
The total energy of detonation      =     -9.904 kJ/cc

JWL Fit results:
E0   =      -10.205 kJ/cc
A    =      1045.25 GPa, B    =     11.08 GPa, C     =         1.56 GPa
R[1] =         4.93,     R[2] =      1.11,     omega =         0.38
RMS fitting error =   0.97 %
```

B.2 BKWC product library

B.2.1 MCX-6002

Product library title: bkwc
Reactant library title: # Version 2.0 by P. Clark Souers

The composition:

Name	% wt.	% mol	% vol	Heat of formation (cal/mol)	Mol. wt.	TMD (g/cc)	
nto	51.00	64.35	48.06	-24140	130.07	1.91	c2h2n4o3
rdx	15.00	11.08	14.95	16496	222.13	1.81	c3h6n6o6
tnt	34.00	24.57	37.00	-15057	227.13	1.65	c7h5n3o6

Density = 1.7997 g/cc Mixture TMD = 1.7997 g/cc % TMD = 100.0000

The C-J condition:

The pressure	=	27.22 GPa
The volume	=	0.423 cc/g
The density	=	2.362 g/cc
The energy	=	3.24 kJ/cc explosive
The temperature	=	3589 K
The shock velocity	=	7.970 mm/us
The particle velocity	=	1.898 mm/us
The speed of sound	=	6.072 mm/us
Gamma	=	3.200

Cylinder runs: % of standards

V/V0 (rel.)	Energy (kJ/cc)	TATB 1.83g/cc	PETN 1.76g/cc	HMX 1.89g/cc	CL-20 2.04g/cc	TRITON 1.70g/cc
1.00	-0.96					
2.20	-5.22	108	82	70	58	120
4.10	-6.24	107	81	70	59	113
6.50	-6.67	107	80	71	60	109
10.00	-6.97	107	80	71	61	106
20.00	-7.31	106	80	72	62	102
40.00	-7.57	106	80	72	62	98
80.00	-7.78	106	80	73	63	94
160.00	-7.94					

Freezing occurred at T = 1800.0 K and relative V = 1.828
The mechanical energy of detonation = -8.167 kJ/cc
The thermal energy of detonation = -0.000 kJ/cc
The total energy of detonation = -8.167 kJ/cc

JWL Fit results:
E0 = -8.574 kJ/cc
A = 870.64 GPa, B = 8.20 GPa, C = 1.14 GPa
R[1] = 4.80, R[2] = 1.07, omega = 0.33
RMS fitting error = 0.89 %

B.2.2 TNT

```
Product library title: bkwc
Reactant library title: # Version 2.0 by P. Clark Souers


The composition:
Name      % wt.   % mol  % vol    Heat of     Mol.   TMD
                                formation     wt.    (g/cc)
                                (cal/mol)
tnt       100.00 100.00 100.00   -15057   227.13     1.65 c7h5n3o6

Density  =  1.6540 g/cc   Mixture TMD =  1.6540 g/cc   % TMD = 100.0000


The C-J condition:
The pressure          =          19.57 GPa
The volume            =          0.454 cc/g
The density           =          2.204 g/cc
The energy            =           2.44 kJ/cc explosive
The temperature       =           3711 K
The shock velocity    =          6.886 mm/us
The particle velocity =          1.719 mm/us
The speed of sound    =          5.167 mm/us
Gamma                 =          3.007


Cylinder runs:             % of standards
  V/V0     Energy    TATB     PETN      HMX     CL-20   TRITON
 (rel.)   (kJ/cc)  1.83g/cc 1.76g/cc 1.89g/cc 2.04g/cc 1.70g/cc
   1.00    -0.74
   2.20    -4.15      86       65       56       46       95
   4.10    -5.13      88       66       58       49       93
   6.50    -5.57      89       67       59       50       91
  10.00    -5.89      90       68       60       51       90
  20.00    -6.28      91       69       62       53       88
  40.00    -6.58      92       69       63       54       85
  80.00    -6.83      93       70       64       55       83
 160.00    -7.05

Freezing occurred at T =     1800.0 K and relative V =   2.399
The mechanical energy of detonation =     -7.526 kJ/cc
The thermal energy of detonation    =     -0.101 kJ/cc
The total energy of detonation      =     -7.627 kJ/cc

JWL Fit results:
E0   =       -7.940 kJ/cc
A    =       531.27 GPa, B    =    6.34 GPa, C     =     1.22 GPa
R[1] =         4.73,     R[2] =    1.06,     omega =     0.30
RMS fitting error =   0.61 %
```

B.2.3 Comp B

```
Product library title: bkwc
Reactant library title: # Version 2.0 by P. Clark Souers

The composition:
Name      % wt.   % mol  % vol    Heat of     Mol.   TMD
                                 formation     wt.    (g/cc)
                                 (cal/mol)
rdx        59.50  60.10  56.69    16496   222.13     1.81 c3h6n6o6
tnt        39.50  39.02  41.09   -15057   227.13     1.65 c7h5n3o6
paraffin    1.00   0.88   2.21  -128107   254.48     0.78 c18h38

Density  =  1.7207 g/cc   Mixture TMD =  1.7207 g/cc   % TMD = 100.0000


The C-J condition:
The pressure          =          26.90 GPa
The volume            =          0.436 cc/g
The density           =          2.292 g/cc
The energy            =           3.35 kJ/cc explosive
The temperature       =           3986 K
The shock velocity    =          7.923 mm/us
The particle velocity =          1.973 mm/us
The speed of sound    =          5.949 mm/us
Gamma                 =          3.015


Cylinder runs:             % of standards
  V/V0     Energy    TATB     PETN      HMX     CL-20   TRITON
 (rel.)   (kJ/cc)  1.83g/cc 1.76g/cc 1.89g/cc 2.04g/cc 1.70g/cc
   1.00    -1.01
   2.20    -5.53     114       87        74       61      127
   4.10    -6.73     116       87        76       64      122
   6.50    -7.24     116       87        77       65      118
  10.00    -7.58     116       87        77       66      116
  20.00    -7.99     116       87        78       67      111
  40.00    -8.29     116       87        79       68      107
  80.00    -8.53     116       87        80       69      104
 160.00    -8.73

Freezing occurred at T =     1800.0 K and relative V =   2.305
The mechanical energy of detonation =     -9.041 kJ/cc
The thermal energy of detonation    =     -0.000 kJ/cc
The total energy of detonation      =     -9.041 kJ/cc

JWL Fit results:
E0   =       -9.369 kJ/cc
A    =       719.53 GPa, B    =     8.70 GPa, C     =         1.54 GPa
R[1] =         4.69,     R[2] =     1.09,     omega =         0.37
RMS fitting error =   0.66 %
```

B.2.4 Octol 60/40

```
Product library title: bkwc

Reactant library title: # Version 2.0 by P. Clark Souers

The composition:
Name      % wt.   % mol  % vol    Heat of     Mol.   TMD
                                formation     wt.    (g/cc)
                                (cal/mol)
hmx        60.00  53.50  56.57    17866   296.17     1.91 c4h8n8o8
tnt        40.00  46.50  43.43   -15057   227.13     1.65 c7h5n3o6


Density  =  1.7960 g/cc   Mixture TMD =  1.7960 g/cc   % TMD = 100.0000


The C-J condition:
The pressure          =          30.16 GPa
The volume            =          0.418 cc/g
The density           =          2.391 g/cc
The energy            =           3.75 kJ/cc explosive
The temperature       =           3998 K
The shock velocity    =          8.214 mm/us
The particle velocity =          2.045 mm/us
The speed of sound    =          6.169 mm/us
Gamma                 =          3.017


Cylinder runs:             % of standards
  V/V0     Energy    TATB     PETN      HMX    CL-20   TRITON
 (rel.)   (kJ/cc)  1.83g/cc 1.76g/cc 1.89g/cc 2.04g/cc 1.70g/cc
   1.00    -1.12
   2.20    -6.02     124        95       81       67      138
   4.10    -7.26     125        94       82       69      132
   6.50    -7.78     125        94       83       70      127
  10.00    -8.13     125        94       83       71      124
  20.00    -8.54     124        93       84       72      119
  40.00    -8.85     124        93       84       73      114
  80.00    -9.09     123        93       85       74      110
 160.00    -9.28

Freezing occurred at T =     1800.0 K and relative V =   2.236
The mechanical energy of detonation =     -9.584 kJ/cc
The thermal energy of detonation    =     -0.000 kJ/cc
The total energy of detonation      =     -9.584 kJ/cc

JWL Fit results:
E0   =       -9.915 kJ/cc
A    =       797.43 GPa, B    =     9.43 GPa, C     =     1.57 GPa
R[1] =         4.66,     R[2] =     1.09,     omega =     0.37
RMS fitting error =   0.64 %
```

Appendix C Relation between barrier thickness and pressure

STANAG 4488 gives the relation between barrier thickness and pressure for HWC donors with density ρ=1.60 g/cm^3. The number of cards is different from what we have used since our card is thicker than those in Figure C.1

ANNEX B to
STANAG 4488
(Edition 2)

TABLE 2. INTERMEDIATE SCALE GAP TEST CALIBRATION DATA
RDX/WAX/GRAPHITE DONOR

# OF CARDS	BARRIER THICKNESS (mm)	PRESSURE (kbar)	# OF CARDS	BARRIER THICKNESS (mm)	PRESSURE (kbar)
10	1.90	185.4	230	43.70	22.8
20	3.80	168.6	235	44.65	21.7
30	5.70	153.2	240	45.60	20.7
40	7.60	139.3	245	46.55	19.7
50	9.50	126.7	250	47.50	18.8
60	11.40	115.1	255	48.45	18.0
70	13.30	104.7	260	49.40	17.1
80	15.20	95.2	265	50.35	16.3
90	17.10	86.5	270	51.30	15.6
100	19.00	78.7	275	52.25	14.8
105	19.95	75.0	280	53.20	14.1
110	20.90	71.5	285	54.15	13.5
115	21.85	68.2	290	55.10	12.9
120	22.80	65.0	295	56.05	12.3
125	23.75	62.0	300	57.00	11.7
130	24.70	59.1	305	57.95	11.1
135	25.65	56.4	310	58.90	10.6
140	26.60	53.7	315	59.85	10.1
145	27.55	51.2	320	60.80	9.7
150	28.50	48.8	325	61.75	9.2
155	29.45	46.6	330	62.70	8.8
160	30.40	44.4	335	63.65	8.4
165	31.35	42.3	340	64.60	8.0
170	32.30	40.4	345	65.55	7.6
175	33.25	38.5	350	66.50	7.2
180	34.20	36.7	355	67.45	6.9
185	35.15	35.0	360	68.40	6.6
190	36.10	33.4	365	69.35	6.3
195	37.05	31.8	370	70.30	6.0
200	38.00	30.3	375	71.25	5.7
205	38.95	28.9	380	72.20	5.4
210	39.90	27.6	385	73.15	5.2
215	40.85	26.3	390	74.10	5.0
220	41.80	25.1	395	75.05	4.7
225	42.75	23.9	400	76.00	4.5

Figure C. 1 The Table shows the connection between barrier thickness and pressure for HWC.