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IM assessment for a state of the art 155mm HE round

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A new 155mm projectile is under development. A state of the art IM 155mm Artillery Projectile requires some major changes.
The projectile design has been optimized in respect of obtaining good IM characteristics, improved fragmentation and long range capability. The long range capability has been achieved by low drag shape and improved base bleed unit.
Literature studies, experiments and calculations of different explosive mixtures have been done to make a choice of composition. Drivers in this study were good IM properties, higher melting point of explosive, good melt cast properties, national production capabilities and filling in own filling facilities.
The ammunition development program back-ground, was the Norwegian/Swedish Archer Program were Norway was responsible for the ammunition. As a result of this an artillery ammunition technology program was run prior to the development program.
This new ammunition is now in the phase of development.
This paper will show the method and discuss the choice of explosive.

1. Introduction

The ammunition development program back-ground, was the Norwegian/Swedish Archer Program were Norway was responsible for the ammunition. As a result of this an artillery ammunition technology program was run prior to the development program.
An important element was to secure national production capabilities and filling in own casting facilities.
In respect of this a new 155mm development program has been established. The main scope of this development program is improved IM properties and performance, STANAG 4439 (1). In this paper we focused on the approach achieving IM capabilities.
This new ammunition is now in the phase of development.

2. Main filling of explosive

Evaluation of alternative fillings

The main filling should be done by a melt-cast process out from the available filling facilities. In addition is melt cast processes recommended when demilitarization shall be performed. After selection of process we performed a literature study to see what type of compositions that could be actual candidates. Theoretical calculations for a large number of combinations of ingredients (2) were performed with Cheetah 2.0 (3). Table 1 shows selected melt cast compositions we brought with us to study IM-properties by use of TEMPER 2.2.2 (4).

Composition/ Ingredients	Ingredients Ratio	CHEETAH Calculations - BKWS Product Library									
			C-J Conditions								
		Composition Density	Pressure	Volume	Density	Energy	Temperature	Shock Velocity	Particle Velocity	Speed of sound	Gamma
		(g/cm^3)	GPa	cc/g	g/cc	kJ/cc exp	K	m/s	m/s	m/s	
NTO/DNAN/RDX	53/32/15	1.7629	24.65	0.437	2.288	2.83	3 425	7 804	1 792	6 012	3.356
NTO/TNT/Al/Wax (XF®-13333)	48/31/14/7	1.7221	19.74	0.447	2.239	2.28	4 286	7 048	1 626	5 422	3.334
NTO/TNT/Al/Wax (XF®-13153)	40/30/20/10	1.6847	16.62	0.457	2.188	1.91	4 536	6 550	1 507	5 043	3.348
NTO/RDX/DNAN/Al	35/14.5/40.5/10	1.7787	23.07	0.432	2.316	2.67	4 252	7 479	1 734	5 745	3.313
NTO/RDX/DNAN/Al	30/22.5/40.5/7	1.7568	23.75	0.436	2.291	2.77	4 058	7 613	1 776	5 838	3.288
COMP B (RDX/TNT/Wax)	59.5/39.5/1	1.7207	27.39	0.443	2.259	3.26	3 939	8 172	1 948	6 225	3.196
IMX-101 (DNAN/NQ/NTO)	43.5/36.8/19.7	1.6890	22.38	0.457	2.187	2.55	3 059	7 655	1 737	5 888	3.389
IMX-104 (NTO/DNAN/RDX)	53/31.7/15.3	1.7637	24.71	0.437	2.289	2.84	3 428	7 811	1 793	6018	3.356
PAX-48 (NTO/DNAN/HMX)	53/35/12	1.7650	24.43	0.437	2.290	2.80	3385	7770	1781	5988	3.362
TNT	100	1.6540	20.75	0.460	2.175	2.49	3 715	7 236	1 734	5 502	3.173

Table 1 Overview actual melt cast explosive candidates

During collection of necessary input data to perform the TEMPER simulations, those combinations without experimental data was excluded and replaced by PBXN-109 with two types of RDX. The final list, Figure 1, contained 10 compositions. For these we performed Fragment Impact (5), Bullet Impact (6) and Sympathetic Reaction (7) simulations with TEMPER 2.2.2 (4). Figure 1 shows the response in Fragment Impact for evaluated compositions in reference 7. The threat is a 18.6 g conical NATO fragment with a velocity of 2530 m/s. Red colour is a *detonation* response and blue is a *no reaction* response. There are large differences in the need of protection for the different explosive fillings to avoid a detonation. Most sensitive compositions are Comp B and PBXN-109 Conv. RDX followed by TNT. Less sensitive is IMX-101 which needs only 4 mm steel protection to avoid a *detonation* response.

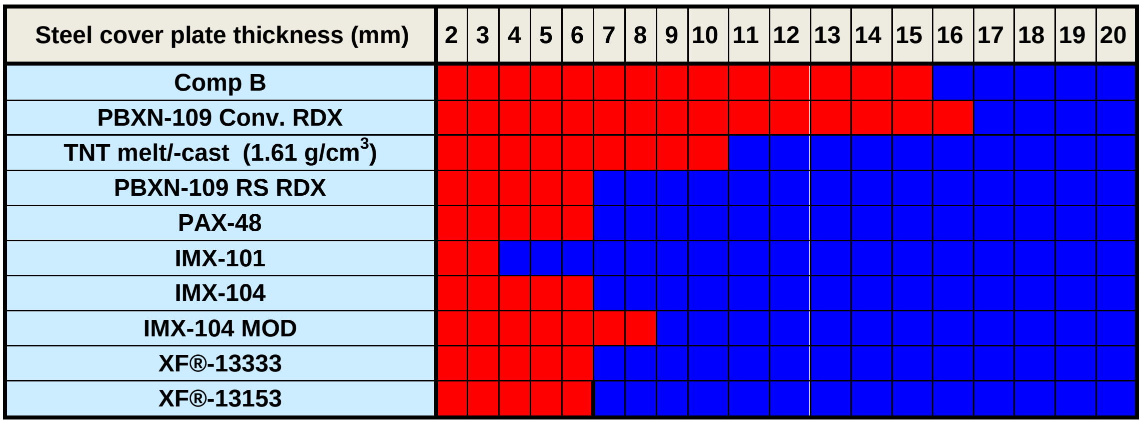
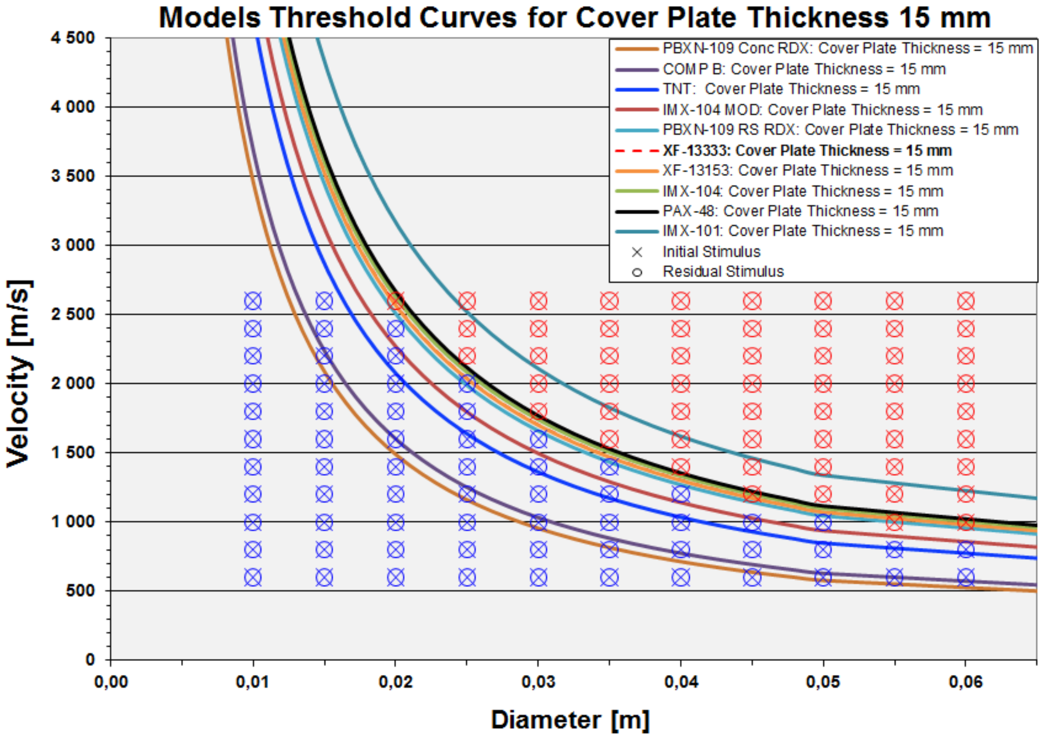


Figure 1 Summary of the response of fragment impact by NATO fragment as function of cover plate thickness for studied compositions

Bullet impact was studied for impact velocities in the range of 600 to 2600 m/s with bullet diameter in the range of 10 to 60 mm. Cover plate thickness ranged from 6 to 20 mm. Figure 2 shows a response plot for 15 mm thick cover plates. Not surprisingly the less sensitive composition is IMX-101. Five other compositions in increasing sensitivity order PAX-48, IMX-104, XF®-13158, XF®-13333 and PBXN-109 RS RDX have approximately the same sensitivity, but it is significant higher than for IMX-101. The two most sensitive compositions are PBXN-109 with conv. RDX and Comp B.



If the bullet diameter/velocity point is above the cover plate threshold curve is the <u>response</u> a <u>detonation</u> (red), placed <u>below</u> give <u>no reaction</u> (blue). The color code is only valid for XF-13333 fillings.

Figure 2 Threshold curves for bullet impact, cover plate thickness 15 mm, of candidate fillings.

In SR the needed protection for a *no reaction* response in the acceptor structure after hit of worst credible (WC) fragments from a detonating donor filled with the same explosive composition varied from 3-6 mm thick steel cover plates for melt casted IMX-101 to 23 mm thick steel cover plate for cast cured PBXN-109 with standard RDX filling. Next to the most insensitive composition IMX-101 followed PAX-48, IMX-104 and PBXN-109 RS-RDX that need protection of 6 to 10 mm thick steel cover plates to respond with a *no reaction*. The next group of compositions to give a *no reaction* response requiring protection from 9 to 13 mm thick steel cover plates includes the melt cast compositions IMX-104 MOD and the XF®-13333. All these compositions except the PBXN-109 with standard RDX will most probably pass the requirements in STANAG 4439 Ed.3 to Sympathetic Reaction test: no response more severe than *burning* if they were filled into 155 mm shells with thin or moderate case thickness. The last three melt-cast compositions TNT, Comp B and XF®-13153 need protection of 13-16 mm thick steel cover plates to respond with a *no reaction* response. With this requirement of protection these melt casted fillings will have problem to obtain a pass in Sympathetic Reaction test when they are filled in thin-walled 155 mm shells.

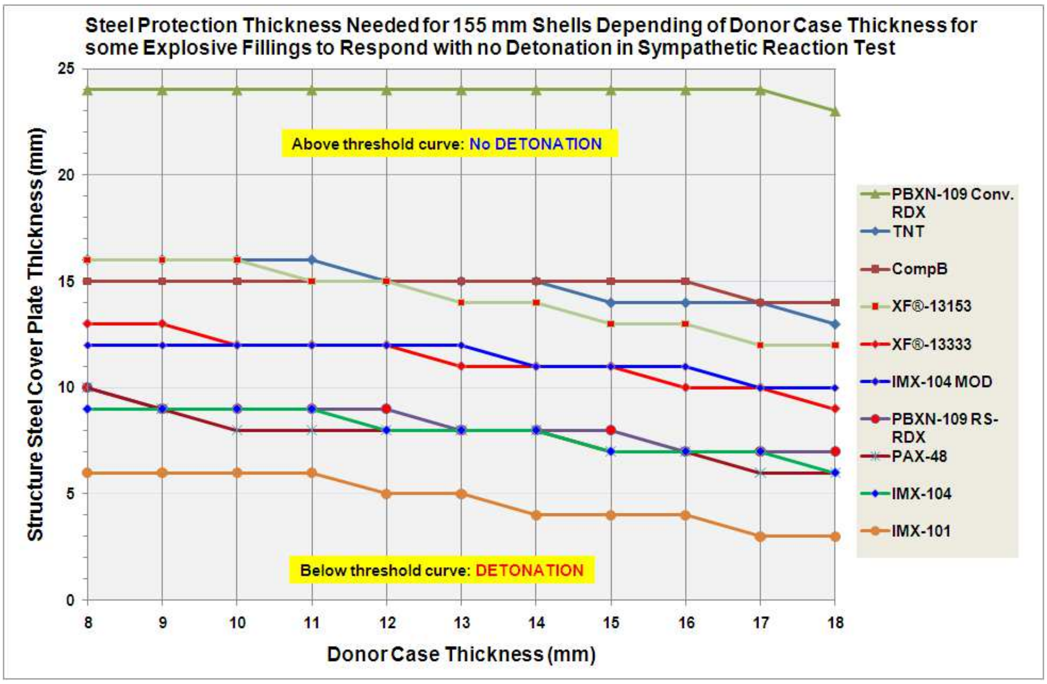


Figure 3 *The Figure shows the threshold curves between detonation and no detonation for different fillings depending on thickness of steel protection and the case thickness of the donor.*

Fragmentation of a generic 155 mm shell with 30 kg steel gave large difference in number and size distribution of the fragments for the different explosive fillings. Total number of fragments for studied compositions : 2216 for XF®-13153, 3272 for XF®-13333, 3773 for TNT,4375 for IMX-104, 5056 for PBXN-109, 5527 for IMX-104 and finally 8491 for the Comp B filling.

Selection of filling compositions

With the obtained result from above studies and the availability of raw materials in cooperation with *Chemring Nobel* it was decided to study 4 compositions two with TNT and two with DNAN as binders. The main filler is NTO for all compositions. Table 2 and Table 3 show the calculated properties of these by use of the Cheetah 2.0 (3).

Composition			Ingredients	CHEETAH Calculations - BKWC Product Library									
				Density	C-J Conditions								
					Pressure	Volume	Density	Energy	Temperature	Shock Velocity	Particle Velocity	Speed of Sound	Gamma
No	Name	Ingredients	Ratio	(g/cm^3)	GPa	cc/g	g/cc	kJ/cc exp	K	m/s	m/s	m/s	
1	MCX 6002	NTO/TNT/RDX	51/34/15	1.7997	27.22	0.423	2.362	3.24	3 589	7 970	1 898	6072	3.200
2	MCX 6100	NTO/DNAN/RDX	53/32/15	1.7629	24.54	0.433	2.309	2.90	3 405	7 671	1 815	5 856	3.226
3	MCX 8001	NTO/TNT/HMX	52/36/12	1.8087	27.27	0.421	2.374	3.25	3 562	7 958	1 895	6 063	3.200
4	MCX 8100	NTO/DNAN/HMX	53/35/12	1.7650	24.19	0.433	2.312	2.86	3 367	7 612	1801	5 811	3.237

Table 2 *Properties at C-J conditions for selected melt cast compositions.*

The two TNT compositions have both better performances than the two DNAN based compositions. All four compositions were manufactured by *Chemring Nobel,* and characterized by determination of detonation velocity and pressure in addition to critical diameter. The final choice of composition for 155 mm filler was done out from several criteria, not only performance and IM-properties. Should we select TNT or

DNAN as binder or should RDX or HMX be the filler was evaluated. In this evaluation was the higher melting point for DNAN than TNT emphasized.

Composition			Ingredients Ratio	Composition Density	Gurney Constant		Mott Constant B
					Cooper	Kamlet/ Finger	
No	Name	Ingredients		(g/cm^3)	(m/s)	(m/s)	kg$^{1/2}$.m$^{-7/6}$
1	MCX 6002	NTO/TNT/RDX	51/34/15	1.7997	2 684	4 405	2.745
2	MCX 6100	NTO/DNAN/RDX	53/32/15	1.7629	2 583	4 234	3.109
3	MCX 8001	NTO/TNT/HMX	52/36/12	1.8087	2 679	4 396	2.739
4	MCX 8100	NTO/DNAN/HMX	53/35/12	1.7650	2 563	4 201	3.162

Table 3 Gurney and Mott constants obtain from Cheetah BKWC product library calculated properties.

The final choice closed to use MCX-6100 as main filling for 155 mm IM-HE-ER. It was decided to qualify this composition according STANAG 4170 (8). MCX-6100 contains the same ingredients as IMX-104 qualified in US (9).

STANAG 4170 qualification

Composition MCX-6100 containing DNAN/NTO/RDX (53/32/15) has been tested with the aim to be qualified for use as main filling in 155mm shells. This work is carried out by *Chemring Nobel, FFI and Nammo Raufoss*. This qualification is not finished, but the intention is to have the composition qualified by the end of the year.

3. Design of shell

Figure 4 shows cutaways of the old, and the new design of the shell. The design is optimized to obtain IM properties and improved performance (10).

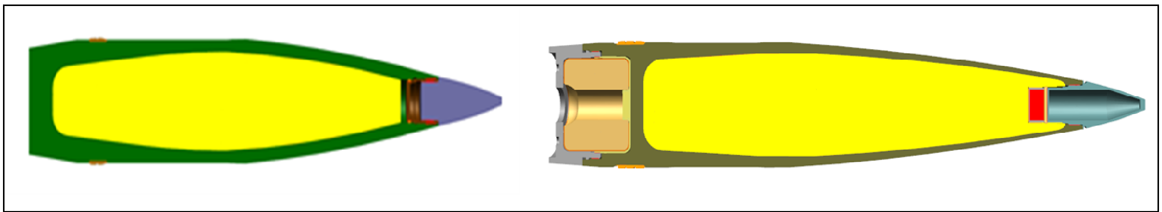


Figure 4 High Explosive Shell NM28 and 155mm IM-HE

4. Testing and characterization of final design

With the design of the shell body and the main explosive filling in place a new phase in the programme started with testing of MCX-6100 composition, filling of shells and testing to qualify the 155 mm IM HE-ER for use in cannon. Shells have been casted for firings, environmental testing, IM-testing and fragmentation testing. Most of these tests have been performed with success. However, in this paper we will focus on reporting on fragmentation of the shell and TEMPER simulations with the final shell body and experimentally obtained properties of the selected main filling MCX-6100.

Characterization of MCX-6100

Detonation velocity and pressure have been determined by use of ionization pins (11), and Plate Dent test for several cylindrical charges (12) Figure 5. Obtained quality of ~~the~~ test items with regard to density has been variable. Measured detonation velocities and pressures are shown in Table 4. Figure 5 shows a plot of detonation velocity as function of charge density. One measurement of MCX-6100 from reference (13) is included.

Table 4 *Overview over experimentally measured detonation velocity and pressure.*

Firing No	Cast No	Charge diameter (mm)	Charge density (g/cm³)	Between pin No	Measuring distance (mm)	Detonation velocity (m/s)	Detonation pressure (kbar)
1	1	35-38	1.74	1-4	210	7260	194
2	8	34.8-38	1.71	1-4	200	7268	191
3	6	35.1-38	1.70	1-3	150	7169	196
4	7	35-38	1.69	1-4	180	7098	179
5							195
6	5	34.7-37.85	1.701	1-5	180	6938	182
8		37-42	1.74	1-5	120	7420	207

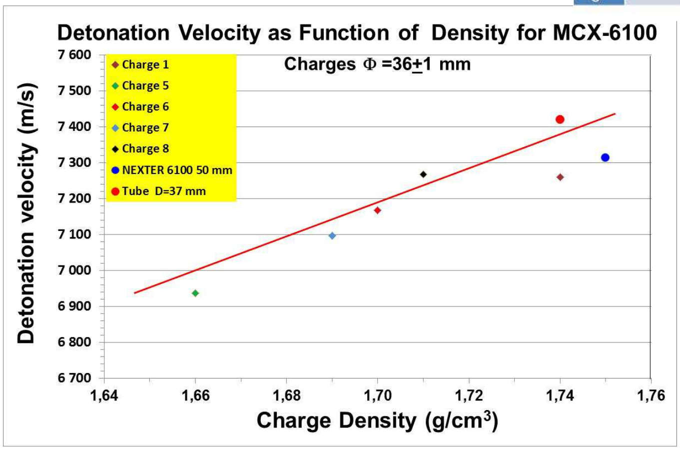


Figure 5 Measured detonation velocities for different charge densities.

Critical diameter has been determined by use of conical charges with diameter increases from 3-30 mm and witness plates. For MCX-6100 has a critical diameter 20 mm.

Shock sensitivity has been determined by Intermediate Scale Gap test (14) for two MCX-6100 Charges filled without use of vacuum during casting. For both charges the fillings contain some inclusions of air in the upper half of the tubes. Due to this, the first tested series was initiated from the bottom, while the second was initiated from the top. Both results are given in Figure 6 and shows different sensitivity. Initiation of the tubes from the top gives significant higher shock sensitivity.

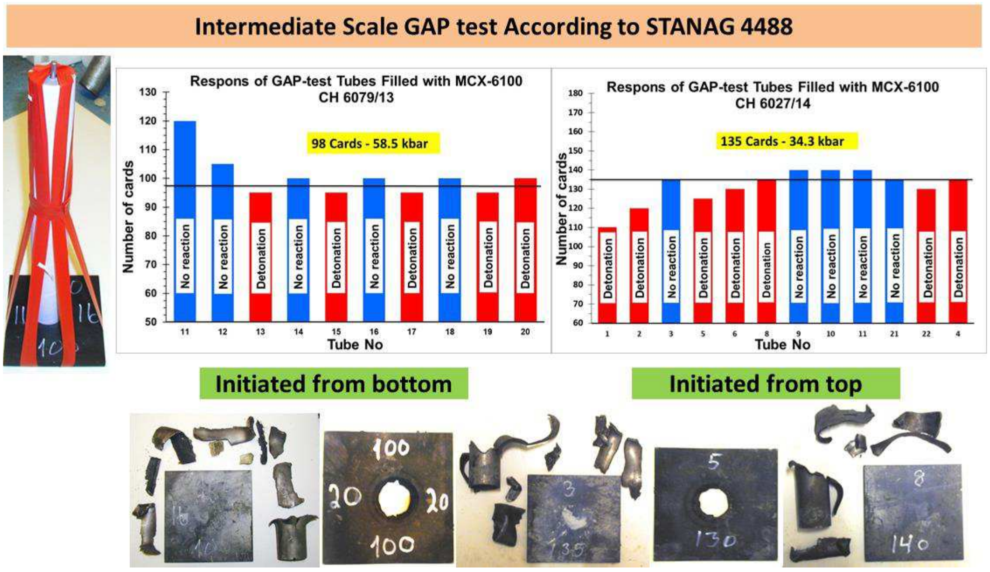


Figure 6 Results of Intermediate Scale GAP test for two different charges of MCX-6100 tested from opposite sides.

Sedimentation study

A well-known property for multi component melt-cast compositions is sedimentation (15). Filled 155 mm shells have been divided longitudinal into two half. Samples

taken from bottom, middle and top of the MCX-6100 filling have been analysed for content to study sedimentation. Figure 7 shows the obtained results for one of this study. In addition to content have density been measured and thereby have the porosity been determined.
Table 5 summarizes these results.
As expected the porosity is highest in the top of the filling.

	RDX	NTO	DNAN	Experimental Density (g/cm^3)	Porosity (%)
Top	15,9	52,7	31,3	1.72	2.52
Middle	14,8	54,7	30,6	1.73	2.18
Bottom	14,7	57,1	28,2	1.75	1.56
Nominal	15.0	53.0	32.0		

Table 5 Analysed content for divided filled with MCX-6100

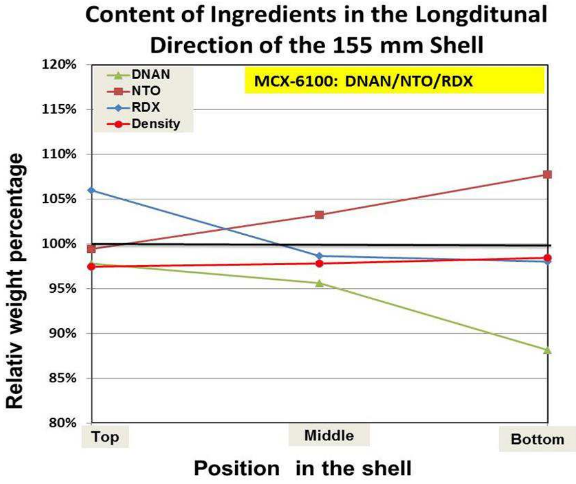


Figure 7 Plot of the ingredients content at different position of divided 155 mm shell.

Observed sedimentation is of same order as other has observed (15). In Table 6 has the effect of sedimentation on fragmentation been calculated by use of TEMPER. In these calculations has detonation velocity and pressure calculated by Cheetah 2.0 been us for the 155 mm fillings. Table 6 last column gives fragmentation results calculated with only experimental measured properties.

Cheetah Calculations for MCX-6100 for divided shell, BKWC								Experimental measured Velocity, Pressure and Density
	Nominal	Top		Middle		Bottom		
TMD (g/cm^3)	1.7629	1.7645		1.7685		1.7777		
Measured density (g/cm^3)			1.72		1.73		1.75	1.74
Pressure (GPa)	24.54	24.72	23.11	24.83	23.43	25.31	24.28	20.7
Velocity (m/s)	7671	7693	7537	7708	7573	7772	7674	7420
Gamma	3.226	3.225	3.228	3.233	3.235	3.243	3.245	3.228
Gurney Cooper (m/s)	2583	2590	2538	2595	2550	2617	2584	2498
Mott constant (kg$^{1/2}$m$^{-7/6}$)	3.105	3.079	3.334	3.062	3.280	2.993	3.145	3.790
C_o (m/s)	2922	2920	2557	2916	2598	2906	2676	2730
S	1.60	1.60	1.83	160	1.80	1.62	1.77	1.72
	Number of fragments							
Envelop thickness 15 mm	5402	5493	4686	5555	4841	5814	5265	3626
Envelop thickness 14 mm	6102	6206	5293	6275	5468	6567	5948	4096
Envelop thickness 13 mm	6951	7069	6029	7147	6229	7481	6775	4665

Table 6 Properties of MCX-6100 filling in different positions of divided 155 mm shell.

Temper simulations

Experimental properties in combination with calculated properties for MCX-6100 have been used to study sensitivity by use of TEMPER. In our simulations we have used the “MSIAC Jacobs-Roslund Vlim” model based on NOL-LSGT (Large Scale GAP Test) threshold values (4, L-139). Other properties needed for material properties description has been calculated by Hugoniot calculation module in NEWGATES V.1-10 (16) and Cheetah 2.0 (3).

Bullet Impact, STANAG 4241

For the BI-test, STANAG 4241 require a 12.7 mm bullet with velocity 830$\underline{+}$ 50 m/s. Triple hits in both main body and the fuze area are required. With TEMPER Bullet Impact threat simulations can use Bullet/Fragment with different size and velocity, but only single hits. For the acceptor the thickness of the shell can be varied to find the limit between *detonation* and *no reaction* response. We have performed simulation with a bullet diameter from 10 mm to 60 mm in step of 5 mm and velocity from 600 m/s to 2600 m/s in step of 200 m/s. Figure 8 summaries the most interesting results. The response depends on the shock sensitivity of the filling. For a single hit even the most sensitive filling are far from giving a *detonation* response. The results show that the sensitivity of the supplementary charge or booster may be more critical for passing the BI-test.

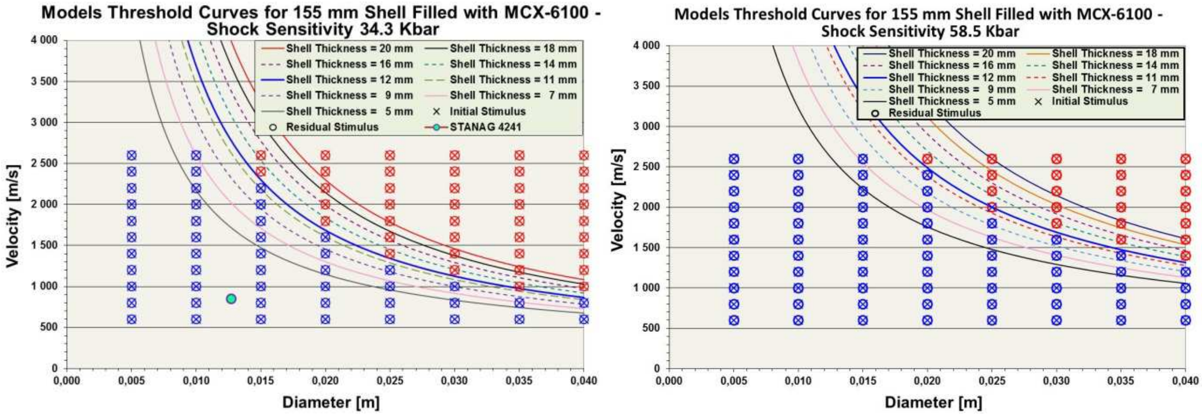


Figure 8 Bullet Impact threshold curves for MCX-6100 of different shock sensitivity.

Fragment Impact, STANAG 4496

STANAG 4496 gives the test condition. Fragment weight is 18.6 g with a diameter of 14.30 mm and conical shape. The velocity is 2530 m/s.

We have performed simulations with acceptor shells filled with MCX-6100 of nominal content and experimental determined shock sensitivities. Figure 9 summarizing the obtained results. With the highest shock sensitivity a *detonation* response is obtained even for a shell thickness of 12 mm. For the lowest shock sensitivity a shell thickness of 6 mm will protect the shell from respond with a *detonation* response.

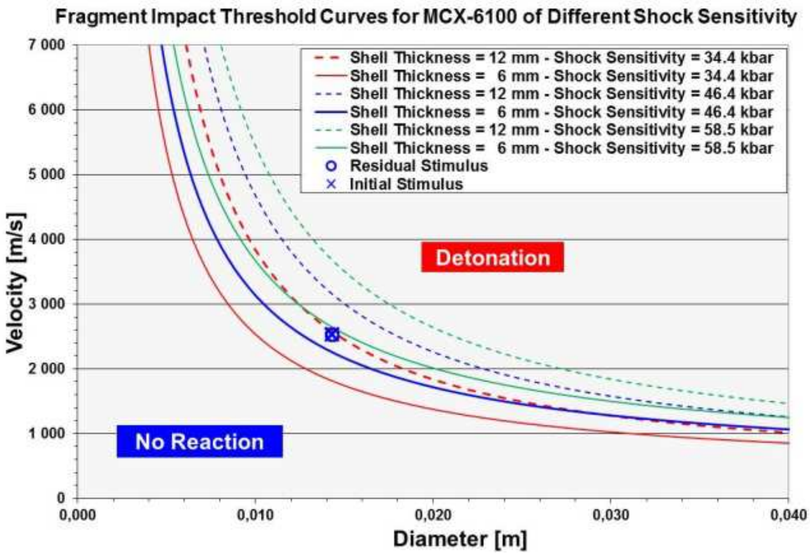


Figure 9 Threshold curves for MCX-6100 with different shock sensitivity for different shell thickness.

Sympathetic reaction, STANAG 4396

In Sympathetic reaction, STANAG 4396, both the acceptor and donor properties are influenced by the main filling. We have carried out simulations with the three analysed contents (Table 5) in both donor and acceptor and two measured shock sensitivities of the acceptor. The three different filler contents of the divided 155 mm shell have been used with calculated performance (Table 6) and experimental density. These simulations were performed to study the effect of sedimentation. For both the donor and acceptor the shell thickness has been 5-20 mm. In addition has simulations with experimentally measured detonation velocity and pressure been performed, last column Table 6.

Figure 10 summaries the simulation results with MXC-6100 content as found in the top of the shell. To avoid a detonation response the acceptor need a protection of 18 mm steel if the filler has a shock sensitivity of 34.3 kbar and only 9 mm with 58.5 kbar.

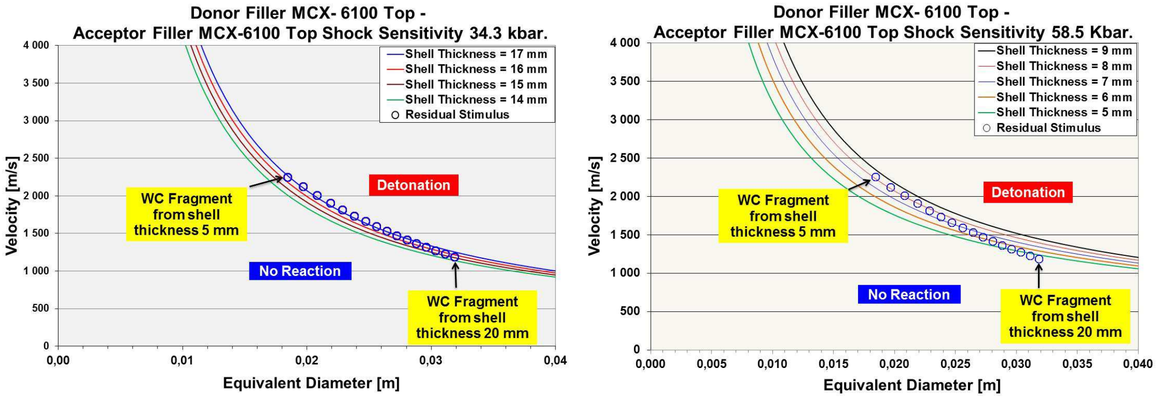


Figure 10 Threshold curves for MCX-6100 Top content and the response for different sensitivity for the acceptor with same content.

Figure 11 summaries the simulations with acceptor and donor with MCX-6100 middle content. To avoid a detonation response the acceptor with 34.3 kbar shock sensitivity filler needs a protection of **18** mm steel, and with the low shock sensitivity filler, 58.5 kbar, the protection need is reduced to **9** mm.

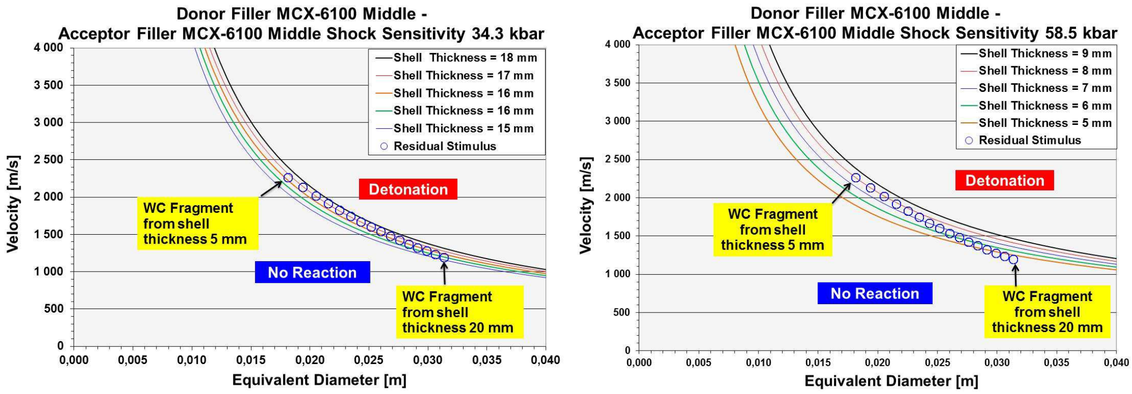


Figure 11 Threshold curves for MCX-6100 Middle content and the response for different sensitivity for the acceptor with same content.

Figure 12 summaries the simulations with MCX-6100 filler with bottom content. With a shock sensitivity of the filling of 34.3 kbar a **17** mm steel protection is needed to avoid a detonation response. With 58.5 kbar sensitivity the need for protection is reduced to **8** mm.

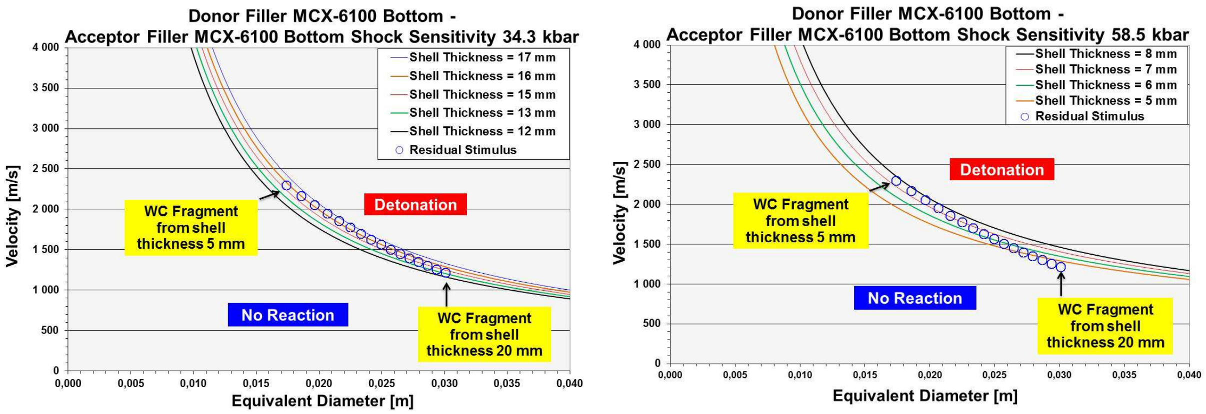


Figure 12 Threshold curves for MCX-6100 bottom content and the response for different sensitivity for the acceptor with same content.

Figure 13 summaries simulations with MCX-6100 nominal content and experimental properties, Table 6. An acceptor shell with shock sensitivity of 34.3 kbar need **22** mm steel protection to not respond with a detonation. With a shock sensitivity of 58.5 kbar the protection is reduced to **11** mm. For both results this is 3-4 mm thicker protection than the values obtained for the theoretical calculated performance.

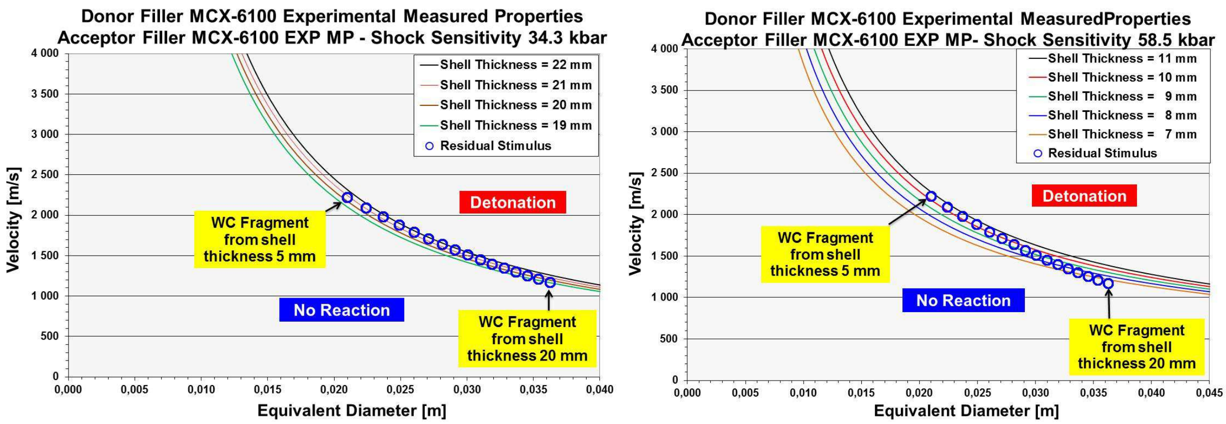


Figure 13 Threshold curves for MCX-6100 nominal content with experimental determined properties and the response for two different shock sensitivity of the acceptor.

From the above simulations two trends is obvious. Variations in content due to sedimentation have an effect on the required protection of $\pm$1 mm for equal responses. The most critical parameter to obtain a *no reaction* response is the shock sensitivity of the acceptor. The observed difference of 10 mm is significant and shows that to obtain good IM properties the shock sensitivity of the main filling should be closer to 58.5 kbar than 34.3 kbar.

IM response engineering tests

Slow Cook Off test has been performed for two shells. The results are not evaluated yet.

Summary

- Composition MCX-6100 selected as the main filler
- Characterization of the composition shows good properties

    - Sedimentation of charges and shell fillings studied
    - Detonation velocity- detonation pressure measured
    - Shock sensitivity
    - Critical diameter
- Qualification, nearly completed
- TEMPER simulations performed with experimental properties of main filling
    - Bullet Impact one hit – good IM response
    - Fragment Impact - good IM response obtainable with low sensitive filling
    - Sympathetic reaction - good IM properties of the main filling should be obtained with shock sensitivity closer to 58.5 kbar than 34.3 kbar.
- From performed TEMPER simulations and full scale IM-tests main filler MCX-6100 looks promising to obtain a 155mm shell that fulfil the IM requirements in STANAG 4439.

Acknowledgement

Thanks to *Chemring Nobel* for casting of test samples.

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