MUNITIONS VULNERABILITY ASSESSMENT ALONG THEIR LIFE CYCLE - METHODS & RESULTS -

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ABSTRACT

Munitions vulnerability assessment is performed during development programs to demonstrate the IMness requirements. Today, many new munitions pass these criteria. Nevertheless, no evaluation is done to prove that munitions keep their IM signature along their life cycle. In this paper, we propose some methods to predict IMness behaviour of ageing munitions. These predictions are based on the knowledge of energetic materials characteristics according to their ageing damages. Through methodologies that allow taking into account various reaction mechanisms; it is possible to estimate the most probable response of ageing munitions. In the future, it would be useful to validate this approach in the aim to increase our confidence in IM assessment all along various life cycles. Nevertheless, since the 90's, Cast Cured Plastic Bonded explosives have been used in many different munitions. Some experimental data are available to demonstrate that the service life can be guaranteed during 20 years as required. This paper describes the methodology and the results concerning the Cast Cured Plastic Bonded Explosives. It has been demonstrated that mechanical and safety properties have not been damaged; and, it can be considered that IM signatures have remained the same.

1. INTRODUCTION

This paper aims at to giving an overview of munitions vulnerability assessment according to ageing conditions. It is true that it is a new subject of interest. It appears naturally a few years after IM introduction in forces. No specific study has already been done as noted during the last MSIAC Workshop [(1)]. It is due to the fact that these munitions are filled with EM reputed to have a good behaviour even after ageing and also that full scale trials are costly. However, vulnerability evaluations can be done through existing methodologies which are usually used during development programs to demonstrate IMness requirements on compliant munitions [(2 to 8)]. In fact, the properties of pristine materials can be replaced by those of aged materials; and following, it is possible to estimate the most probable response of ageing munitions [(9)]. This builds up the first paper part.

For all the munitions (warheads, shaped charges, torpedoes, underwater mines, etc...), the required service can reach 20 years. During this period, the munitions have to keep their performances and their safety properties [(10, 11)]. EURENCO (previously SNPE) which manufactures since many years Cast Cured Plastic Bonded Explosives has been led to conduct some ageing characterization programs concerning these compositions. Two classic ageing conditions were used: 20 & 60°C during up to 11 & 8 years respectively. It has been demonstrated for these compositions that the mechanical and safety properties have been preserved [12]; and it can be considered that the IM signatures have remained the same.

2. PREDICTIVE METHODOLOGIES AND ANALYSIS TOOLS

SNPE policy is to develop predictive methodologies based on small scale testing and on databases associated to numerical simulations. It is done in the aim to reduce the number of full scale tests and to increase confidence in their results by influence analysis of parameters. These methodologies are based on the entire knowledge of EM reaction mechanisms. They are more or less precise according to the state-of-art, but they have been validated up to the full scale test for each vulnerability threat. They are recognized by French authorities DGA / IPE through vulnerability reports issued to obtain the MURAT Labels: 1, 2 or 3 stars (the 3 stars label is compliant with full requirements of STANAG 4439).

Some methodologies are available for each safety or vulnerability threat, intense shocks (sympathetic detonation, shaped charge attack, …), impacts (bullets, fragments, drops, …), thermal threats (fast & slow cook-off), electrical stimuli (electrostatic, electromagnetic, lightning, …). By this way, we can answer to each case of relevant Hazard Assessment Protocols by TTCP or NIMIC [13, 14]. SNPE has also developed similar tools. It is not possible to detail every methodology in the present paper, so we give Thermal Threat example to support approach explanations (see figure A).

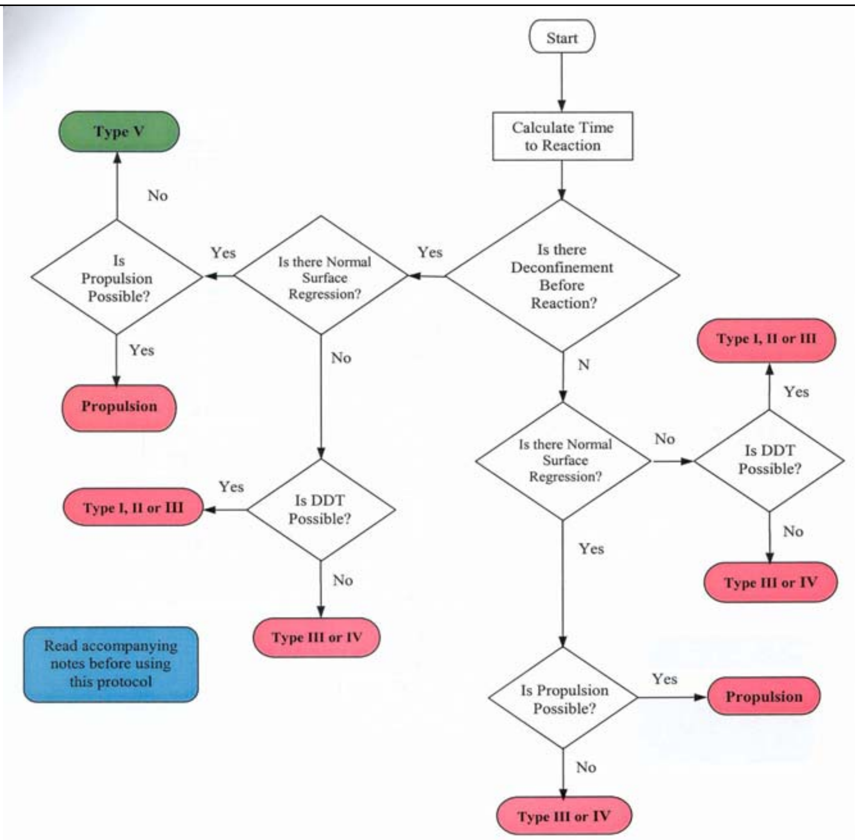


Figure A : NIMIC Flow Chart for thermal threats

We can understand that behind every question several parameters must be taken into account. For example, question "is DDT possible?" forces to consider when an EM grain is damaged: - Which is its specific surface? - Which is its burning surface? - Which is pressure increasing rate? - Which is confinement pressure burst? - … ……

THERMAL THREAT EXAMPLE:

In the figure B, SNPE's methodological tool pack for "thermal threat" is described:

- Orange cases are entry data and output predictions,
- Yellow cases summarise chemical & physical phenomena involved,
- Green cases concern experimental characterisation,
- Blue cases list numerical simulation capabilities.

In fact, to model the mechanisms which are indicated in yellow cases, some experimental characterizations are conducted and the results are the entry data for numerical simulations. Of course, numerical simulation accuracy must be improved to discriminate type III to type V reactions. Green cases can contain a lot of parameters that should be determined. The list of vulnerability monitoring parameters is issued from these cases.
For example, for EM submitted to a thermal threat, it is necessary to determine EM ignition temperature, but also self-heating kinetic, density, specific heat, thermal conductivity, mechanical properties, burning speed, friability value …

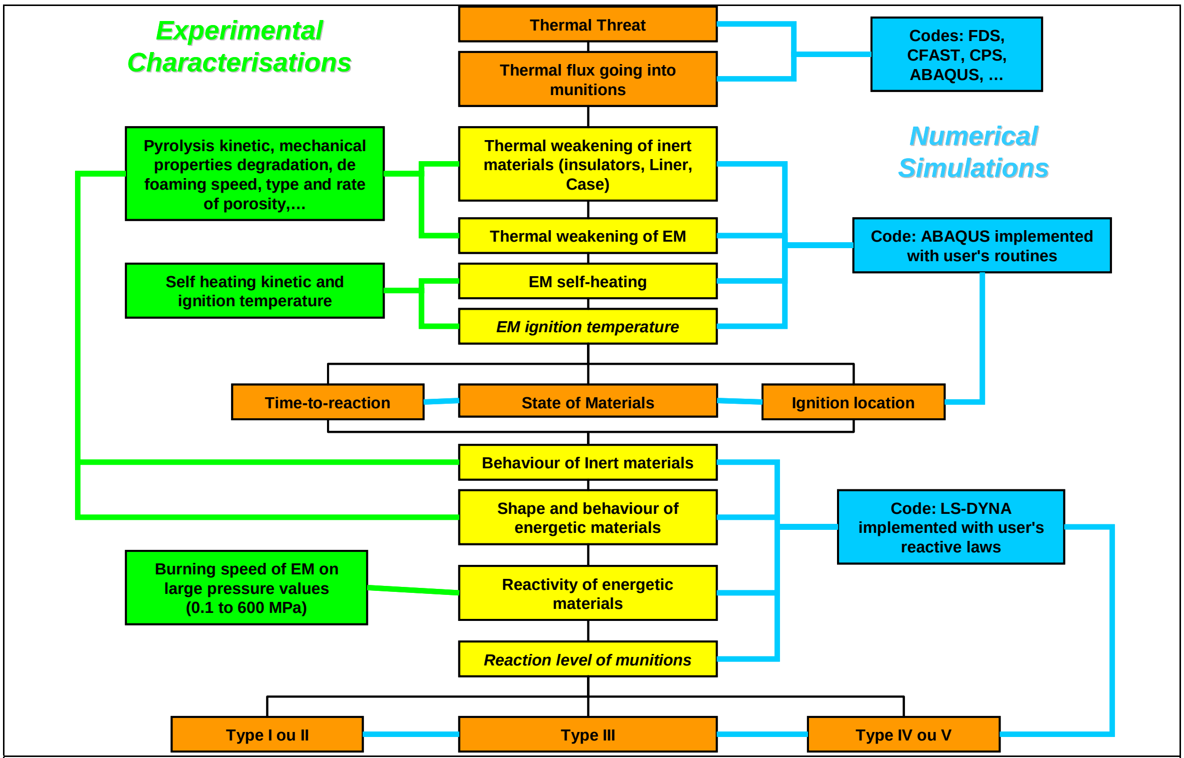


Figure B : SNPE's Methodology Tools for thermal threats

Few examples can be given:

- EM ignition temperature (STANAG 4491 B1) is an important parameter, as it imposes reaction time of munitions. It is possible to determine its variability between batches, and it is also possible to quantify effects of ageing damages concerning this parameter (nevertheless for this parameter, expected ageing changes would be slight). Through that way, it is feasible to predict reaction time of an ageing munitions submitted to a thermal threat. For 2 & 3 stars MURAT Labels; time-to-reaction to fast cook-off must exceed five minutes, so it is necessary that munitions pass this threshold.
- For time-to-reaction criteria, several others parameters are important and concern inert parts of munitions (case, insulation, liner): density, specific heat, thermal conductivity, radiative emissivity, softening kinetic, melt temperature, flammability of their pyrolysis gas…

- Concerning reaction type, immediately comes in mind: burning speed from ambient to high pressure (AOP-7- 302.02.003) and friability (AOP-7-201.08.004 or UN7c) ii)), pressure rupture of different parts of munitions case. Friability is a parameter which is checked in ageing monitoring program conducted by SNPE [15].
- But other parameters can be important for violence level of reaction. It is necessary to have a good knowledge of the reaction scenario to detect them. For example, for determining all origins of burning surface increase: one of them is the quality of sticking between EM grain and thermal insulation or case. We have verified this fact through comparison between different liners. So, it is possible to check sticking quality during time on accelerated ageing samples. Following, it is possible to determine if munitions response will be the same when submitted to life cycle conditions.

3. VULNERABILITY MONITORING PARAMETERS

Previous examples show that it is necessary to have an entire knowledge of EM behaviour and munitions architecture characteristics. It is not easy to list all vulnerability monitoring parameters; a Fault Tree Analysis is useful to do that. But, when this work has been achieved, it is possible to determine on samples the effect of ageing and to extrapolate to munitions IM signature.
In the table below (extract), a tentative list of such parameters is given [9]. These are classified by munitions parts and mechanisms involved by vulnerability threats. This list is not exhaustive, it would be defined for each munitions even if the large majority of parameters are the same.

Munitions parts	**Monitoring Parameters**	**Comments**
Munitions case	Thermal conductivity	Thermal aspects
	Radiative emissivity	Especially for Fast Cook-off
	Pressure burst at high loading rates according to temperature	For all threats
	Shock Hugoniot	For intense shocks
	Melt temperature	Especially for Fast Cook-off
	………..	………..
Thermal insulation / liner	Specific heat	Thermal aspects
	Shock Hugoniot	For intense shocks
	Melt temperature	Especially for Fast Cook-off
	Flammability temperature	Especially for Fast Cook-off
	Pyrolysis kinetic	Thermal aspects
	………..	………..
Energetic materials (main charge, booster, …)	Density	
	Pressure / Time threshold for detonation	For intense shocks
	Detonation critical diameter	For intense shocks
	Friability	For all threats
	Pyrolysis kinetic	Thermal aspects
	Self-heating kinetic	For slow cook-off
	Pressure / Damage dependant burning rate	For all threats
	………..	………..
Architecture parameters	Sticking resistance (case, thermal insulation, EM grain…)	
	Liquid tightness	Especially for melt cast explosives
	Protective cap characteristics	Nozzle, venting device
	Characteristics of mitigant devices	Functioning guarantee
	Characteristics of Ignition / initiation devices	Under all aspects
	……………	………..

Figure C : Tentative list of vulnerability monitoring parameters [9] (extract)

4. REACTION MECHANISMS REVIEW AND DISCUSSIONS

In previous paragraph, the influent parameters have been listed. Implicitly, everyone knows reactive mechanisms which are involved for EM reactivity or case burst pressure. Nevertheless, it is necessary to examine ageing influence on the material properties which are quantified by the vulnerability monitoring parameters. EM property changes due to ageing can be more or less important. Concerning mechanical properties, these changes can be crucial because poor properties can outcome porosity and/or cracks generation. Thus, EM reactivity can be drastically increased; it is quantified through apparent burning rate. At the opposite, stored energy in EM is still constant because ingredients are still present in same quantity. So, it could be resumed by the idea: When the EM grain reacts, it is the same energy which is available, but the delivery time depends on damages due to threat effects which are added to ageing changes. Then, for example, the ignition temperature parameter would be constant, except if unstable specie has been accidentally created by unexpected self-degradation or by interaction with other materials.

Shock-to-detonation transition: The main parameter is the threshold detonation obtained through the Card Gap Test. It is easy to check it according to an accelerated ageing, it is sufficient to detect any change. These changes could be provoked by shock Hugoniot evolution or internal porosity. Through SNPE's experience, cast PBX and rocket propellants keep their standard value during specified ageing. Often, changes in barrier thickness are limited to test variability.

Deflagration-to-detonation transition and violent reactions: Deflagration-to-detonation transition concerns powder products, and compact material which are fragmented by mechanical threats. This is facilitated when mechanical properties are insufficient or degraded by ageing. Laboratory scale pertinent tests are the Friability and the strand-burner under high pressure (up to 600 MPa). Through SNPE's experience, Cast Cured PBX and rocket propellants keep their standard values during specified ageing.

Thermo-ignition due to slow Cook-off: Thermo-ignition occurs in an EM which is completely thermally damaged, so none added effect of ageing is expected. Unless some interactions with others materials should generate new species that modify self-heating kinetic. In this precise domain, knowledge is slight, but existing results do not show any little changes for self-heating kinetic. These characterizations were done through self ignition temperature and unconfined thermo-ignition test.

Case properties degradation: This subject has two sides, if case mechanical resistance is degraded, and then given protection to EM grains against shocks is reduced. But on the other end, if case burst pressure is lower; it is favourable to moderate burning reactions.

Thermal insulation or liner degradation: Degradation of these parts would have bad effects, indeed, the given protection to EM grain will be reduced and this can play a mitigant role when EM will react. It is the case, when the sticking has disappeared; the burning surface is increased many times with the worst consequences on burning pressure increase.

Discussions: For many development programs, some Life Duration Assessments are conducted in the aim to demonstrate the required Life Duration. These are done under accelerated ageing conditions. It could be relatively affordable to conduct complementary small scale testing in the aim to obtain the data to perform some response predictions to vulnerability threats according to ageing.

The list of most important vulnerability monitoring parameters would be established taking into account specificity of each munitions. These parameters are useful along life cycle of munitions:

- During the design phase, these parameters allow to do some definition choices,
- During the manufacture step, these parameters would be checked to improve item quality confidence,
- For the IMness demonstration, these parameters increase confidence in a reduced number of full scale tests,
- For life duration assessment, these parameters should guarantee keeping of IM signature along life cycle.

5. PROPERTIES STUDIES OF AGEING CAST CURED PBX

EURENCO (previously SNPE) which manufactures since many years Cast Cured PBX has been led to conduct some ageing characterization programs concerning these compositions [12]. These characterizations were focused on classic mechanical properties and main safety characteristics as requested in NATO standards AOP 7 & 15 [10, 11]. The only vulnerability trials were the Bullet Impact tests which have been conducted on SNPE's vehicle (1.1 litres). Indeed, the today concerns about the IM signature according to the life cycle have not been a priority during the 90's.
The ageing conditions were 20 & 60°C during up to 11 & 8 years respectively. The PBX blocks were packaged in closed plastic bags. Before experiments, samples were extracted by machining from block cores, avoiding to use the layers near from grain surface. For Bullet impact tests the explosive grains were set up directly. The main characteristics of tested compositions are listed in the A.

Purpose	Reference	Filler content	Binder	Filler (s)	Density	D (m/s)	EIDS
Booster	**B2188A**	84	HTPB	HMX/PETN	1.62	7900	No
	B2238A	78	HTPB	RDX	1.57	8040	No
Blast or underwater effects	**B2211D**	88	HTPB	RDX/AP/Al	1.81	5500	Yes
	B2245B	88	HTPB	RDX/NTO/AP/Al	1.81	5150	Yes
Ballistic effects	**ORA86B**	86	PU	HMX	1.70	8360	No
	B2214B	84	HTPB	HMX/NTO	1.63	7450	Yes
	HBu88A	88	HTPB	RDX	1.63	8110	No

Table A: Formulation of the PBX

Experimental Characterizations:

The mechanical properties have been assessed by:

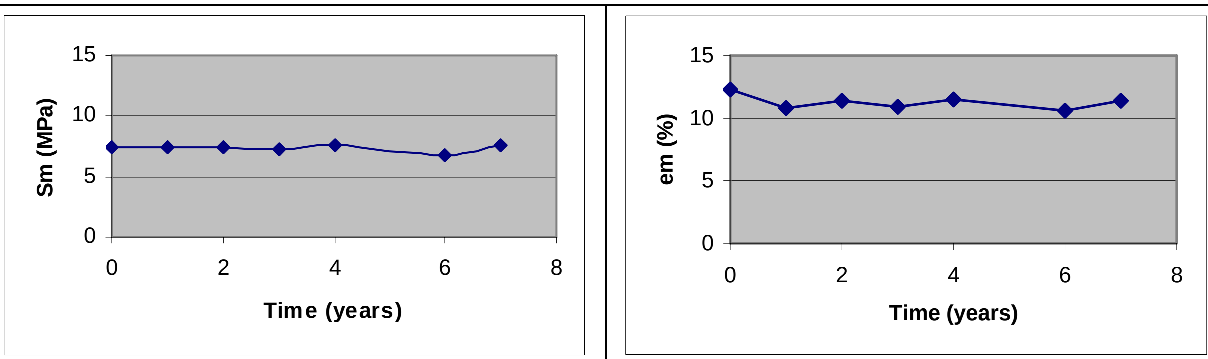
- Uniaxial tensile according to AOP 7 STANAG 4506 with CRB dog bone samples, crosshead of 50 mm/min, temperature 20°C.
- Uniaxial compression according to AOP 7 STANAG 4443 with cubic samples (10 mm x 10 mm x 10 mm), crosshead of 1 mm/min, temperature 20°C.

In addition these mechanical properties, for some points, safety and vulnerability tests are performed:

- Impact sensitivity (BAM) according to STANAG 4489C.
- Friction sensitivity (BAM) according to STANAG 4487A.
- Shock sensitivity (Intermediate Scale Gap Test) according to STANAG 4488B.
- Friability test according to AOP 7 (201.08.004) or UN 7c)ii).
- Burning under high pressure: this test allows determining the pressure frontier between the layer by layer combustion propagation and cracking combustion which can outcome any deflagration-to-detonation transition. This frontier is called Break Pressure. It is performed in a closed vessel with a static resistance to rupture of 1000 MPa
- 12.7 mm bullet impact in vehicle according to AOP 7 (201.05.002).

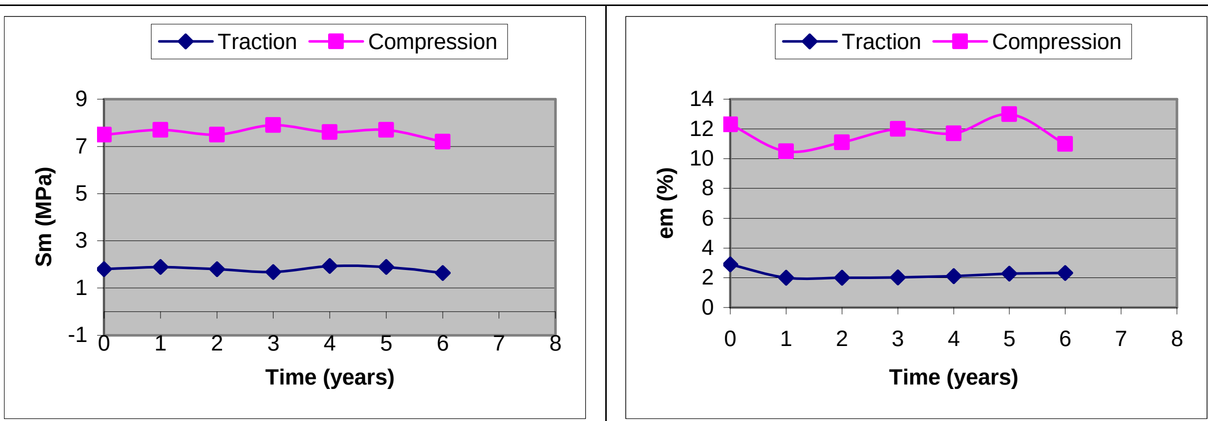
Results and discussions:

The results of the tests carried out for the investigation are presented. For two compositions, (ORA86B and B2214) the results are presented in details. For the other compositions, only summary of results and the main conclusions are given.



S_m versus time | e_m versus time

Figure D : ORA 86 B submitted to 60°C



S_m versus time | e_m versus time

Figure E : ORA 86 B submitted to 20°C

Temperatures	**Properties**	S_m	e_m
60°C	Compression	-0.032 t + 7.49	0.040 t + 10.93
20°C	Tensile	+0.026 t + 1.90	+0.025 t + 2.02
	Compression	-0.111 t + 7.98	0.046 t + 11.27

Table B: Maximum stress and deformation versus time

Duration (years) at 20°C	**Friability (dP/dt)max**	**Combustion under high pressure**	**Bullet impact (V = 850 m/s)**
0	5	No pressure break	Pneumatic explosion
1	6.5	No pressure break	Pneumatic explosion
5	7.3	No pressure break	Pneumatic explosion
11	7.3	No pressure break	Pneumatic explosion

Table C: Effects on the friability, combustion and bullet impact tests

About ORA86B, at 60°C or 20°C, no significant evolution is noted for mechanical properties, as shown on curves S_m and e_m as a function of time (Figures D & E). The equations have been calculated without the value of the pristine composition because preliminary evolutions are due to some continuing crosslinking reactions (Table B). This absence of evolution is

confirmed by the test results: Friability, Combustion under high pressure and bullet Impact (table C)
About B2214B, at 60°C or 20°C, no significant evolution is noted on mechanical properties, or for the various tests: Friability, Combustion under high pressure and bullet Impact, Friction, Impact, Gap test (Tables D & E).

Duration (months)	Tensile			Friability dP/dt (MPa/ms)	Combustion under high pressure	Bullet impact V = 850 m/s	Friction (N)	Impact (J)	Gap test (cards)
	S_m (MPa)	E (MPa)	e_m (%)						
0	0.55	12.2	12.5	0.3	No break	Combustion	> 353	47	15
3	0.63	13.8	12.2						
6	0.64	15.0	10.6	0.3			> 353	35	20
9	0.73	16.9	9.9						
12	0.80	17.9	11.9						
18	0.80	22.3	10.2						
24	0.77	18.0	9.3	0.3	No break	Combustion	> 353	41	10

Table D: B2214B Effect of storage time at 60°C on the different properties

Duration (years)	Tensile test			Friability dP/dt (MPa/ms)	Combustion under high pressure	Bullet impact
	S_m (MPa)	E (MPa)	e_m (%)			
0	0.55	12.2	12.5	0.3	No break	Combustion
2	0.54	8.8	11.7			
3	0.60	13.2	12.7			
4.5	0.57	10.5	12.1			
5	0.66	10.5	10.6	0.3	No break	Combustion
6	0.69	10.6	12.8			

Table E: B2214B Effect of storage time at 20°C on the different properties

At 60°C (table F), for HBu88A, B2188A and B2238 compositions, the slopes of curves are weak which means that the variations of stress and elongation are negligible. Thus, for example these variations (in percentage) are lower than 13 % after 5 years at 60°C. For B2211D and B2245 compositions, the slopes lead to a significant decrease of stress and elongation, about 30 % after 5 years. These compositions present a slight softening during the ageing.

Compositions	Duration (years)	Mechanical test	$S_m = f(t)$	$e_m = f(t)$
HBu88A	**8**	compression	+ 0.066 t + 2.54	+ 0.090 t + 6.29
B2188A	**7**	compression	+ 0.038 t + 2.47	- 0.313 t + 12.20
B2211D	**4**	compression	- 0.410 t + 6.50	- 2.963 t + 42.11
B2238	**3**	compression	- 0.0136 t + 3.02	- 0.606 t + 26.08
B2245	**2**	tensile	- 0.090 t + 1.31	- 0.886 t + 11.65

Table F: Effect of storage time at 60°C on the mechanical properties

At 20°C (Table G), the same trends are observed that is: for HBu88A, B2188A and B2238 compositions, no significant evolution of the stress and elongation after 10 years, for B2211D composition, a slight softening, for B2245 composition, contrary to 60°C, a hardening is observed. In conclusion, the mechanical properties of the compositions filled with RDX, HMX, HMX/PETN and HMX/NTO remain stable during the aging at 20°C and 60°C. The compositions which show a hardening or a softening during the ageing are those filled with AP/Al.
Indeed, except the variations observed during the first month, the values of dP/dt versus time are practically constant. The result variability is usually +/- 10% (Table H).

Compositions	Duration (years)	Mechanical test	$S_m = f(t)$	$e_m = f(t)$
HBu88A	11	compression	+ 0.004 t + 2.57	+ 0.135 t + 6.89
B2188A	11	compression	- 0.004 t + 2.28	- 0.077 t + 12.91
B2211D	8	compression	- 0.021 t + 4.68	- 0.028 t + 42.56
B2238	8	compression	+ 0.043 t +2.70	+ 0.577 t + 22.85
B2245	6	tensile	+ 0.078 t + 0.74	+ 1.040 t + 7.42

Table G: Effect of storage time at 20°C on the mechanical properties

Time (years)		0	0.5	1	2	3	6	11
HBu88A	**20°C**	17		30		23	25.3	33.5
B2188A		18		22.5		22	23.1	20.0
B2211D		3.8		4.0			4.2	
B2238		2.5		3.2		3.8	3.6	
B2245		3.6					2.1	
B2245	**60°C**	3.6	4.0		3.7			

Table H: Effect of storage time on friability test: dP/dt_{max} (MPa/ms)

Except the B2188A, for the other compositions the type of the reaction is pneumatic explosion (table I). For the B2188A, the results are scattered.

Time (years)		0	1	2	6	11
HBu88A	**20°C**	Pneumatic explosion	Pneumatic explosion		Pneumatic explosion	
B2188A		No reaction	Pneumatic explosion		Deflagration	Pneumatic explosion
B2211D		Pneumatic explosion	Pneumatic explosion		Pneumatic explosion.	
B2238		Pneumatic explosion	Pneumatic explosion		Pneumatic explosion	
B2245	**60°C**	Pneumatic explosion		Pneumatic explosion		

Table I: Effect of storage time on bullet impact test

Time (years)		0	1	2	6	11
HBu88B	**20°C**	No break	No break		No break	No break
B2188A		420	405		320	460
B2211D		No break	No break		No break	
B2238		No break	No break		No break	
B2245	**60°C**	No break		No break		

Table J: Effect of storage time on combustion test (MPa)

No break of the burning rate is observed except for B2188A composition where a break is observed for a pressure close to 400 MPa. This corresponds to transition from parallel layer burning to cracking combustion, which is able to provoke violent reactions. It is the same composition that presents a behaviour scattered at the bullet impact. It can be noted that it is the only composition that contains PETN filler.

6. CONCLUSIONS

This paper presents many experimental results concerning the industrial Cast Cured PBX compositions. During 90's, the needs have been more the safety concerns and the suitability for service than the IM signature according to life cycle. The methodology has been based essentially on the changes in mechanical properties of the compositions. Then, it is regarded if these changes influence the response of the materials at the safety and Bullet Impact tests. The results of seven industrial PBX are reported. The compositions filled with RDX, HMX, HMX/NTO and HMX/PETN do not show significant variations of their mechanical properties during the ageing. The compositions filled with RDX/AP/Al and RDX/NTO/AP/Al present slight variations of mechanical properties, hardening or softening, which induce no evolution of the safety and Bullet Impact test results. This family of explosive compositions is particularly stable in the time and in temperature.

Moreover, this paper presents methodologies allowing to predict munitions responses to each vulnerability trial. Some proposals are given to extend them to IMness assessing according to life cycles. Indeed, the properties of ageing EM can be compared to databases and introduced in numerical simulations tools. This approach has not been fully validated yet. Nevertheless, many arguments and previous works show that it is possible to predict IM signature through small scale testing. Then, this approach would be conducted to complete the demonstration of IM advantages. At least, it is necessary to consider the whole munitions (liner…) and not the EM grains alone to deliver pertinent assessments.

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