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Literature review and background material

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Summary

Insensitive munitions are less prone to inadvertent ignition by exterior stimuli such as fire, bullet impact or fragment impact than older munition types. Hence, insensitive munitions are safer to store and to use in weapons and on platforms. However if the insensitivity properties change when the munitions are ageing, the munitions may become significantly less safe to store and use, something which may lead to enhanced hazards and serious accidents. In order to maintain the operational and logistic advantages with IM, the influence of ageing of IM must be addressed, and dedicated testing and surveillance procedures need to be developed.

This report contains a literature survey of ageing aspects of insensitive munitions and consists of three main parts. First a short list of munitions incidents and accidents in Sweden is presented and compared to U.S. accidents. Then the ageing of munitions and energetic materials is reviewed, followed by a part on testing and analysis of IM properties.

Keywords: Insensitive munitions, IM, ageing,

Sammanfattning

Lågkänslig ammunition (eng. Insensitive Munitions, IM) är mindre utsatt för oavsiktlig initiering av yttre stimuli, som brand, projektilträff, eller splitterträff, än äldre typer av ammunition. Därför är lågkänslig ammunition säkrare vid lagring eller vid användning i vapen och på plattformar. Lågkänslighetsegenskaperna kan dock förändras när ammunitionen åldras, vilket kan leda till ökade risker och allvarliga olyckor. För att bibehålla de operativa och logistiska fördelarna med lågkänslig ammunition måste man beakta åldrandets inflytande på lågkänslig ammunition och dedicerade testmetoder och övervakningsprocedurer behöver utvecklas.

Denna rapport innehåller en litteraturstudie av åldringsaspekter för lågkänslig ammunition och består av tre delar. Först presenteras en kort lista med ammunitions-olyckor och tillbud i Sverige och en jämförelse görs med amerikanska olyckor. Sedan ges en överblick av åldring av ammunition och energetiska material, följd av en del om testning och analys av lågkänslighetsegenskaper.

Nyckelord: Lågkänslig ammunition, IM, åldrande

Contents

1 Introduction

"Insensitive Munitions" (IM) or "Munitions à risques atténués" (MURAT) is defined in the NATO standard STANAG 4439 edition 2 [1] as:

> *"Munitions which reliably fulfill their performance, readiness and operational requirements on demand and which minimize the probability of inadvertent initiation and severity of subsequent collateral damage to weapon platforms, logistic systems and personnel when subjected to selected accidental and combat threats."*

The incentive for developing IM is a number of more or less serious accidents or incidents, in which munition has ignited due to exterior stimuli, such as heat or penetrating fragments, and caused damage to personnel and equipment. Such stimuli can occur during any part of the munitions life cycle, including production, storage, transport, and operative usage on a military platform. IM requirements are usually imposed on development of new munition, but older munition is often exempted from satisfying IM requirements [2].

Analyses of accidents/incidents with munitions which have occurred in the world have been categorized into a list of six types of threats, encompassing the different types of exterior stimuli which can initiate or aggravate an accident or incident. The types of threats are given in the NATO Allied Ordnance Publication AOP-39 Edition 2 [3] as:

1. Magazine/store fire or aircraft/vehicle fuel fire (Fast Heating)
2. Fire in an adjacent magazine, store or vehicle (Slow Heating)
3. Small arms attack (Bullet Impact)
4. Fragmenting munitions attack (Fragment Impact)
5. Shaped charge weapon attack (Shaped Charge Jet Impact)
6. Most severe reaction of same munition in magazine, store, aircraft or vehicle (Sympathetic Reaction)

There exist extensions of this standard threat list, such as in the French MURAT classification, which in addition to the six threats above also includes Heavy fragment impact [4], and U.S. MIL-STD-2105C also treats Spall impact, which concerns impact on the munition of hot spall fragments produced in a shaped charge event [5]. Other hazards which sometimes are discussed in IM context are Drop and Electrical stimuli [4].

The types of reaction levels (i.e. responses to stimuli) which can occur in munitions subjected to exterior stimuli are defined in STANAG 4439 [1] and in the Military Standard MIL-STD-2105C [5], and are named:

- Type I Detonation
- Type II Partial Detonation
- Type III Explosion
- Type IV Deflagration
- Type V Burning
- No Reaction.

In order for a particular munition to be classified as IM, it has to show a response no more severe than a specific type for each of the identified threats, as specified in STANAG 4439 [1]. There are standardized tests for each of the threats given above. Assessment that a particular munition fulfils these requirements can be made by adhering to procedures described in detail in AOP-39 [3] and in MIL-STD-2105C [5]. The entire set of responses to the standard threats is called the IM signature of the munition type tested.

A number of different techniques can be employed to obtain IM properties for a particular munition [6]:

- Use less sensitive energetic materials in high explosives, gun and rocket propellant or pyrotechnics
- Munitions system design (munition cases, thermal/shock mitigation, venting, and thermal management)
- Ordnance protection (container design, shielding, packaging, and barrier)

There are several advantages with IM usage, apart from the obvious reduced risk of self destruction of weapon and platform. IM can be a force multiplier, enabling a military platform to stay longer on a mission, or can offer the opportunity to increase the deployment of a weapon due to the reduced threat to the surrounding community or infrastructure, and finally IM can be more cost effective and efficient to transport, store and handle due to the reduced hazard classification [3]. Examples of operational, logistic and cost benefits of IM are given by MacKichan et al. [7].

However, if the IM properties are degraded due to ageing during storage or transportation, there is a definite risk that the munitions will no longer fulfil the requirements for IM classification, and hence incur serious danger on its transportation or usage. In order to maintain the operational and logistic advantages with IM, the influence of ageing of IM must be addressed, and dedicated testing and surveillance procedures need to be developed.

This report is intended to provide background material for a study of impact of ageing on Insensitive Munitions in a joint EDA-project. The objective is a survey of the state of the art concerning:

- Analysis of incidents or accidents at munition storage
- Effect of ageing on IM signature (thermal, mechanical threats …)
- Safety/Vulnerability requirements
- Surveillance techniques
- Small and large scale testing of ageing phenomena
- Chemistry of ageing
- Novel techniques for life cycle evaluation

The report is mainly a literature survey and consists of three main parts. First a short list of munitions incidents and accidents in Sweden is presented and compared to U.S. accidents. Then the ageing of munitions and energetic materials is reviewed, followed by a part on testing and analysis of IM properties.

2 Swedish munitions accidents and incidents

Fortunately, there are few reported accidents or incidents with munition or explosives in Sweden. There are no known Swedish incidents with insensitive munitions (IM). The following short list gives examples of accidents and incidents with stored munition in Sweden since WWII, and has been kindly provided by Christer Daun at the Swedish Defence Materiel Administration (FMV):

1. A delivery in 1946 of charges for 15 cm howitzers contained gun propellant consisting of 98.2 - 99 % nitro cellulose (NC) and 1 - 1.8 % diphenylamine stabilizer (DPA) (named Lng1-6 m/39). At the time of delivery, the propellant could be kept at 65ºC for 690 days without developing red-fumes.
   At a propellant surveillance test in 1962, the corresponding time was > 210 days. At that time, the requirements for approval was:

• > 180 days	approved
• 120-180 days	approved, but prioritized for use
• 60-120 days	discard
• < 60 days	discard immediately

   At a propellant surveillance test in 1964 propellant lots were found where red-fumes were developed already after 67 days, and at a renewed control samples with times as low as 26 days were found. "All" propellant was immediately discarded. In 1968, four charges which for some reason had been put aside self-ignited in storage. It was only through a brave and rapid action on behalf of an employee that a catastrophe could be prevented.
2. Anti-aircraft ammunition of German origin, manufactured in 1938, consisted of 20 mm grenades (SLSGR m/39).). The grenades were provided with a fuse with a detonator cord (ÖHK SAR m/39). At a test firing in 1951, an early ignition occurred due to transformation of lead azide into cupric azide in the detonator in up to 36 % of all cases. During dismantling of the fuses, an operator was touching the centrifugal bolt when the detonator ignited. Since the safe-arm device was dismantled from the grenade the explosive material was at a safe distance and no further reaction occurred. This type of ammunition was discarded in 1951.
3. An accident occurred in October 1971 when a 40 mm grenade (SLHPGR M/43) primed with FBAR43 detonated during mounting. Six people were injured at the accident, of which one later died. In the following analysis of cause of accident it was found that the primary explosives in the detonator had ignited. One cause could have been formation of cupric azide (from lead azide) which was found in the detonating cord. A definitive cause could not be established.
4. There have been a number of incidents with smoke grenades (RÖKHGR m/56), filled with white phosphorous that has self-ignited. When the steel casing of the grenade corrodes, the white phosphorous comes in contact with air and self-ignites.

A list of significant weapon and explosives accidents experienced by the U.S. military since 1960 is given in the DoD Acquisition Managers Handbook for IM [6], table 1-1.

The Swedish accidents/incidents reported on have occurred due to ageing in storage, in which chemical reactions have resulted in changed sensitivity of the explosive material, or in which corrosion of protective shells has degraded the safety of the munition. Most U.S. accidents have occurred during handling or operative use and have been caused by petroleum fires or rocket impacts at the munition.

For comparison, a review of major accidents with commercial explosives and physical explosions, some naturally occurring, can be found in Leiber and Doherty [8].

3 Ageing of Munitions and Energetic Materials

One way to achieve IM-properties in a weapon system is to replace the energetic material with a less sensitive one. There are a number of energetic materials, such as TATB (triaminotrinitrobenzene), TEX (dinitrodiazatetraoxaisowurtzitan), NTO (nitrotriazolone), FOX-7 (diaminodinitroeten), and I-RDX (insensitive cyclotrimethylenetrinitramine) which are considerably less sensitive than TNT (trinitrotoluene), RDX (hexogen), and HMX (octogen) [9,10,11,12,13,14,15,16]. A list of major reduced vulnerability high explosives and propellants is given in tables 12 - 14 in Watt et al. [17]. Examples of IM for different weapon systems are given in table 4-3 in the DoD handbook [6].

Although some types of insensitive munitions have been produced for over 20 years, the long term ageing of the IM and constituent materials is not completely investigated. Practical experience of long term ageing is scarce, but laboratory tests with accelerated ageing are being performed.

The ageing processes of munitions depend not only on the stability of the energetic materials used, but also on the compatibility with other materials used in the munition (e.g. casing), and on the storage environment [17]. Ageing can have negative effects on IM, either by deteriorating the IM properties, and hence increase the risks for serious accidents or incidents, or by reducing the service life expectancy of IM compared to (non-IM) standard munition. Hence, stability surveillance may be an unavoidable part of IM maintenance.

Ageing processes can be subdivided into chemical, physical and mechanical. Chemical ageing can be initiated or accelerated in storage or transport by exposure of the munition or energetic material to a number of environmental factors, such as heat, ultraviolet radiation, gamma radiation, or solvents (including water and petroleum products) [18]. Migration of ingredient substances can lead to physical ageing, with inhomogeneous material properties and possibly also varying sensitivity within a charge. Mechanical vibrations or impact can introduce cracks or fissures [17], which may alter the performance at a later time, and possibly also degrade the IM properties.

In this report we only focus on the chemical stability and ageing of energetic materials, explosives, propellants, and compositions.

3.1 Chemistry aspects of ageing

The energetic fillers RDX, HMX, TATB, NTO, and FOX-7 exhibit good thermal chemical stability [17]. Ammonium perchlorate and ammonium nitrate are prone to undergo recrystallisation in the presence of moisture. TATB shows a dramatic colour change when exposed to UV radiation [18], which indicates a chemical reaction.

The binder HTPB (hydroxy terminated polybutadiene), which has a double bond in the chain structure, experiences an ageing mechanism in the presence of free oxygen, which increases the cross-link density of the binder with decreased strain capability and increased crack formation as a result [17]. HTPB can be replaced with HTPE (hydroxy terminated polyether) for IM-purposes. Since HTPE has no double bonds, it is much less prone to oxidative cross-linking and crack formation. HTPE also has a milder response to slow cook-off and bullet impact than HTPB [19]. However, Bu-NENA is often used as energetic plasticizer in combination with HTPE, and with MNA (methyl-nitroaniline) as stabilizer. Depletion of MNA due to removal of nitrogen oxides from nitrate ester degradation leads to rapid gas generation and propellant softening. High temperature studies show that MNA concentration below 0.1% means end of the service-life, and that MNA depletion can be measured during propellant aging to estimate service-life [20].

RDX/NC/CAB (Cellulose Acetate Butyrate) based LOVA (LOw Vulnerability Ammunition) propellants have been seen to experience stabilization periods of up to 20 weeks with gradually decreasing breech pressure in storage after manufacture [21]. This was attributed to decreasing levels of residual solvent in propellant grains, accompanied by co-migration and accumulation of plasticizer at the grain surfaces. It was also observed that residual solvent may oxidize and generate organic acids. The proposed remedy was development of a drying cycle to remove all residual solvent before storage.

Increased humidity and temperature, as in accelerated ageing chambers, has been seen to induce reverse curing reactions in the polymers polyNIMMO and polyGLYN, resulting in softening of the polymer matrix, something which can reduce the vulnerability [17]. For HMX/polymer compositions, a positive correlation between polymer matrix density and shock sensitivity has been observed [22].

Accelerated ageing during a 12 month period of ARX-4024, a melt-cast explosive of 35% TNT and 65% bimodal NTO (nitrotriazolone) intended as a replacement for Composition B in Australian munitions, showed less loss of TNT by sublimation than Composition B and negligible change in impact, friction, electrostatic discharge, and temperature sensitivity [23].

Another alternative to Composition B is PBX formulations based on FOX-7, which in a castable composition with polyGLYN has shown excellent thermal stability at 65ºC [24].

To summarize, the following ageing mechanisms have been observed to occur in energetic materials used in munitions:

- Reverse curing reactions and binder softening
- Increased cross-linking and binder hardening
- Auto-catalysis of nitrate esters resulting in auto-ignition
- Depletion of stabilizers accompanied by increased gas generation
- Oxidative cross-linking in materials with double bonds
- Plasticizer migration
- Moisture absorption and recrystallisation leading to decomposition

The MSIAC report by Watt et al. [17] contains further information on ageing effects and munitions safety.

3.2 Effects of ageing on IM signature

The IM signature of a munitions object is given as the set of responses, as defined in STANAG 4439 [1], to the set of defined threats, as given in AOP-39 [3]. During ageing, this set of responses may change. In addition, the effects of ageing on performance must always be considered, since degraded performance is a crucial reason for discarding aged munitions.

Hardening due to increased binder cross-linking [17], loss of residual solvent [21] or other processes can make the material more brittle and sensitive to shocks and vibrations. Cracks formed in the material may result in a more violent response in the case of intended or accidental ignition.

Evaporation of substances may create voids, which can form hot spots and become sources of ignition when the munition is exposed to shock. Hence lack of chemical and physical stability as a result of ageing can lead to deterioration of IM properties of munition that has initially been classified as IM.

Migration of substances, such as plasticisers, may introduce inhomogeneities, with varying physical properties throughout a charge. This can also include variations in IM properties, such as shock or temperature sensitivity. There are several examples in which ageing degrades the IM signature, but in some cases, such as with reverse curing of the polymers polyNIMMO and polyGLYN, ageing may improve the IM signature [17].

4 Testing and analysis of IM properties

Assessment that a particular munition type qualifies as IM is obtained by performing a predefined set of tests. The number of tests and the test practice varies between nations, but most IM test programs are based on NATO STANAG 4439 edition 2 [1] and AOP-39 Edition 2 [3]. For each of the six threats defined in AOP-39, there is a standard test intended for classification of a munition based on the type of response.

However, since these publications do not contain exact and detailed instructions on how to perform the tests, national testing practices and methodologies differ [25]. The MIL-STD-2105C contains descriptions of U.S. DoD test procedures and test setups [5]. Figure 1 shows a flowchart for IM testing and classification based on STANAG 4439 and AOP-39.

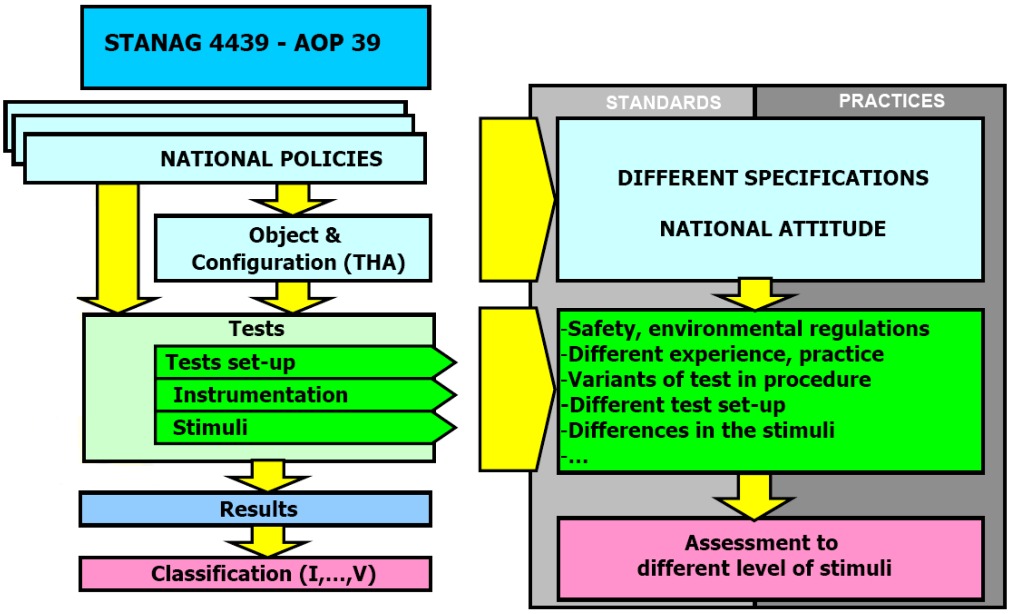

Figure 1 Flowchart for IM testing and classification, based on STANAG 4439 and AOP-39 [25]

The standard tests used in IM assessment give as result the IM signature for the tested munition at a specific time during the munitions life-cycle. Since ageing processes have the potential to change the IM signature, renewed testing at regular intervals and/or monitoring of the physical and chemical status of the munition is required.

There exist standard procedures to achieve accelerated ageing of explosive materials and complete munitions, but the results must be used with caution since accelerated ageing can give rise to ageing mechanisms not seen at natural ageing [17]. Accelerated ageing can also be used to mimic the effects of environmental conditions to which munitions may be subjected when used operatively in geographic regions for which the munition was not developed.

In addition to the standard IM assessment procedures, other tests may be required to monitor the ageing processes in munitions. Examples are depletion or migration of substances from explosive charges, pressure changes in casings, and storage temperature and humidity changes.

Each IM assessment procedure and surveillance technique requires criteria for actions to be taken when a change is detected in the monitored properties. In many cases semiempirically based modelling of the ageing processes can be helpful in determining the test intervals.

4.1 Small and large scale testing of ageing munitions

4.1.1 Accelerated ageing

Accelerated ageing is achieved by exposing the munition studied to an elevated temperature for a specified time interval. Usually temperatures between 50ºC and 70ºC are used. The correlation between temperature, exposure time and corresponding storage time varies depending on the rate of the degrading process which depends on the chemical composition, stabilizer used, etc. [17].

Accelerated ageing can be performed at constant conditions or at varying conditions, usually in cyclic variations representing yearly or diurnal variations or changes in exposure due to interleaved periods of handling, transport, and storage. In addition to elevated temperature, other environmental conditions, such as relative humidity, presence of oxygen, or exposure to vibrations or shock, can be controlled in accelerated ageing procedures [17].

A theoretical relation for the temperature dependence of chemical reactions is given by the Arrhenius formula [17,26]:

$$k = A_0 \cdot e^{-E_a / RT} \qquad (1)$$

where k is a rate constant, which for slow reactions equals the reaction rate,
A_0 is a material constant,
E_a is the activation energy of the reaction,
T is temperature in K,
R is the gas constant, 8.314 J/mol·K.

Activation energies may be determined by microcalorimetry or by fitting equation (1) to experimental ageing data at several elevated temperatures.

For a single chemical reaction occurring in storage and in an accelerated ageing procedure, we obtain the acceleration factor K_T for the accelerated ageing as:

$$K_T = \exp\left(\frac{E_a}{R}\left(\frac{1}{T_s} - \frac{1}{T_a}\right)\right) \qquad (2)$$

where T_s is the storage temperature,
T_a is the acceleration temperature.

Equation (2) is an idealisation, valid if there are no phase transformations occurring in the temperature interval between T_s and T_a and the reactions do not include transport phenomena. In the latter case, diffusion processes may limit the reaction rates.

Equations (1) and (2) may be used in complex ageing processes, involving many reactions with different activation energies, to indicate the temperature dependence [26]. Then the activation energy E_a used will be an effective value for the entire ageing process.

Extensions of equation (2) can be used in accelerated ageing processes, when other environmental conditions than temperature are varied. For example, if both temperature and relative humidity (RH) are used as acceleration parameters, one of the following equations may be used within a limited parameter range [26]

$$K_T = \exp\left(\frac{E_a}{R}\left(\frac{1}{T_s} - \frac{1}{T_a}\right) + E_f\left(\frac{1}{RH_s} - \frac{1}{RH_a}\right)\right) \qquad (3)$$

$$K_T = \left(\frac{RH_a}{RH_s}\right)^a \exp\left(\frac{E_a}{R}\left(\frac{1}{T_s} - \frac{1}{T_a}\right)\right) \qquad (4)$$

where the material constants E_f and a can be found by fitting the equations to experimental data.

4.1.2 Standard IM-test procedures

Corresponding to each of the standard threats described in AOP-39, there is a dedicated test procedure which is supposed to mimic the threat situation. Table 1 summarises the standard threats, corresponding IM requirement, and gives a short description of the baseline threat range. More detailed descriptions of the test procedures are given in AOP-39 [3], MSIAC L-113 [17], MIL-STD-2105C [5], and other documents.

These IM-property tests are by nature destructive and require munition objects taken from the storage for testing. To get good statistics, each test usually has to be repeated with several objects. Several statistical techniques can be used in the analysis of the experimental data [27].

Since performing large scale tests is expensive and cumbersome, it is generally desirable to reduce the scale and complexity while retaining relevance. Most of these standard tests can be performed on a small scale in laboratory setups, but the sympathetic reaction test is usually difficult to perform except with at least a few full scale munition objects.

Table 1 Standard threat, IM requirement, and baseline threat range [3].

THREAT	REQUIREMENT	BASELINE THREAT RANGE
Magazine/store fire or aircraft/vehicle fuel fire (Fast Heating)	No response more severe than Type V (Burning)	Average temperature between 550ºC and 850ºC until all munitions reactions completed. 550ºC reached within 30 s from ignition.
Fire in an adjacent magazine, store or vehicle (Slow Heating)	No response more severe than Type V (Burning)	Between 1ºC and 30ºC per hour heating rate from ambient temperature.
Small arms attack (Bullet Impact)	No response more severe than Type V (Burning)	From one to three 12,7 mm AP round, velocity from 400 m/s to 850 m/s.
Fragmenting munitions attack (Fragment Impact)	No response more severe than Type V (Burning)	Steel fragment from 15 g with velocity up to 2600 m/s and 65 g with velocity up to 2200 m/s.
Shaped charge weapon attack (Shaped Charge Jet Impact)	No response more severe than Type III (Explosion)	Shaped charge caliber up to 85 mm.
Most severe reaction same munition in magazine, store, aircraft or vehicle (Sympathetic Reaction)	No propagation of reaction more severe than Type III (Explosion)	Detonation of donor in appropriate configuration.

An example of IM-testing of a rocket motor exposed to fuel fire, bullet impact, and slow heating is given by Jameson [28].

An attempt to numerically simulate fragment impact on IM is described by Lam et al. [29].

Table 2 lists the documents describing the performance of the standard IM tests and documents containing detailed procedures for assessment.

Table 2 Documents describing the performance and method of assessment for the standard IM tests

IM test	Performance	Assessment
Fast heating / Fast cook-off (FCO)	STANAG 4240	AOP-39
Slow heating / Slow cook-off (SCO)	STANAG 4382	AOP-39
Bullet impact (BI)	STANAG 4241	AOP-39
Fragment impact (FI)	STANAG 4496	AOP-39
Shaped charge jet impact (SCJI)	STANAG 4526	AOP-39
Spall impact test	MIL-STD-2105C	MIL-STD-2105C
Sympathetic reaction (SR)	STANAG 4396	AOP-39

4.1.3 Tests for chemical stability, compatibility and performance

To attain slow ageing, it is necessary to only utilize stable materials and materials that are compatible with each other. A safe standard procedure is to use materials which are known to be compatible with each other [17], but since many insensitive energetic materials are comparatively new and not enough tested, and since we are likely to see many new materials developed in the future, further testing the chemical stability and compatibility with different materials used in the development of IM will be essential. Compatibility with other materials proposed for the intended usage is regularly tested during the development of a new energetic material. The stability with regard to IM signature needs further consideration.

STANAG 4147 defines a number of standard chemical compatibility tests for ammunition components and explosives [30]:

Test 1 Procedure A - The Vacuum Stability Test (Manometer Method)
Procedure B - The Vacuum Stability Test (Transducer Method)

Test 2 The Heat Flow Calorimetry Test

Test 3 Procedure A - Dynamic Thermogravimetry (TGA)
Procedure B - Isothermal Thermogravimetry (TGA)
Procedure C - Determination of the Kinetics of Decomposition

Test 4 Differential Scanning Calorimetry

Test 5 Chemical Analysis
Procedure A - Chemical Analysis - Assessment of the Compatibility of Ammunition Component Materials with Nitrate D-Ester Based Propellants
Procedure B - Chemical Analysis - Assessment of the Compatibility of Ammunition Component Materials with Lead and Silver Azide

In addition to these tests, MSIAC L-113 [17] lists the following materials compatibility tests with references:

- Isothermal microcalorimetry
- Accelerated Rate Calorimeter (ARC)
- Heat Flow Calorimeter (HFC)
- Chemiluminescence

A comparison between different methods for stability testing of propellants is given in table 28 in MSIAC L-113 [17]. The tests included are:

- Dutch Weight test
- Bergman-Junk test
- Weight loss test Surveillance test
- Γxc
- Heat flow calorimetry
- Stabilizer consumption
- Molecular mass depletion
- Chemiluminescence
- Thermogravimetry

In addition to tests of chemical stability and compatibility, it is also necessary to test the influence ageing has on performance, for which a number of well-established procedures are used. MSIAC L-113 [17] gives short descriptions of the following standard tests:

- Closed Vessel Test
  Used to measure the heat of explosion, and hence the energy content of ageing gun propellants. Final pressures and burn rates at different pressures and temperatures are obtained from pressure measurements in the closed vessel.
- Pin Hydrodynamic Test
  Monitors changes in implosion behaviour. Measures the elapsed time from initiation until a high explosive drives a mock pit into an array of timing pins of known length and location. This gives information about the temporal and spatial uniformity of the implosion. In this way, the influence of density variations, voids, and cracks can be detected.
- Snowball Test
  Used to test the initiation chain. Includes streak camera photography of the detonation wave on the outer surface of a hemispherical charge which is initiated in the centre.
- Detonation Profile Test
  Investigates the effect of ageing on detonation behaviour. Uses a streak camera to measure the velocity and curvature of a detonation wave from a cylindrical charge. The sample diameter is close to the failure diameter, for which changes in detonation velocity or detonation front curvature is expected to show high sensitivity to ageing effects.

4.1.4 Other tests

MIL-STD-2105C [5] lists the following additional tests which can be included in a test plan for munitions and weapon systems, depending on the intended usage and expected ambient environment characteristics:

Acceleration
Accidental Release
Acoustical
Aerodynamic Heating
Atmospheric Lightning
Altitude
Catapult and Arrested Landing
Double Feed of Ammunition
Drop
Dust
Electromagnetic Interference
Electromagnetic Radiation
Electromagnetic Pulse
Electromagnetic Vulnerability
Electrostatic Discharge
Explosive Atmosphere
Faulty Unit
Flooding
Fungus
HERO - Hazards of Electromagnetic Radiation to Ordnance
Hot Gun Cook-Off
Humidity
Jettison
Jolt
Jumble
Leak Detection - Halogen-helium
Leakage - Immersion
Materials Compatibility
Muzzle Impact/Impact Safe Distance
Pressurization
Proof Pressure Firings
Radiography
Rain
Salt Fog
Shock
Solar Radiation - Sunshine
Space Simulation - Unmanned Test
Static Detonator Safety
Time to Airburst
Toxicity
Vibration

Burgess et al. [18] include exposure to heat, ultraviolet (UV) and gamma (γ) radiation, and to solvents as important factors affecting the ageing of plastic bonded explosives.

In addition to the standard threats to IM, as given in Table 1, there are new emerging threats to IM, such as [31]:

- Warheads with Explosively Formed Penetrators (EFP),
- Intentional Electromagnetic Interference (IEMI),
- Thermobaric Warheads,
- Terrorist Specific Threats: Improvised Explosive Devices (IEDs)

There is naturally a need to develop standardized test procedures for these and other emerging threats.

4.2 Surveillance techniques

It is standard practice to remove munition samples and explosives from long term storage at regular intervals and analyse the influence of ageing by the test methods mentioned in the preceding sections. Usually these tests are destructive for the samples selected. Such a test scheme gives a statistical estimate of the ageing of the munitions in that particular batch and under the specific storage conditions of that storage.

In addition to intermittent destructive tests, there is also a need for non-destructive monitoring of munitions ageing. This makes it possible to follow a specific munitions item through its entire life, from manufacture to discarding and destruction. Non-destructive surveillance techniques are well suited for data logging and remote computerized monitoring using automated radio link communication.

MSIAC L-113 lists the following techniques for non-destructive evaluation of munitions ageing [17]:

Current techniques

X-ray Radiography

Computerised Axial Tomography (CAT) or Computed Tomography (CT)

Ultrasonics

Laser Ultrasonic System

Thermographics

Penetrometer

Borescope

Embedded Sensors (temperature, pressure, humidity etc.)

Dataloggers

Novel/emerging techniques

Ultrasonic Resonance Spectroscopy

Shearography

Neutron Radiography

Embedded Sensors (MEMS and SMART layer)

Bond Stress & Temperature Sensor

Nano-Sensors

Munition Health Monitoring Activities (dataloggers for temperature, humidity, shock, vibration and pressure)

As discussed in chapter 3, depletion of stabilizers is an important ageing phenomenon. In nitrate ester based compositions stabilizer depletion can lead to self-ignition, but stabilizer depletion and possibly linked migration of other substances also has the potential of affecting the IM properties of munitions in storage and transport. Hence depletion of stabilizers may be one property requiring monitoring. One possibility is by regular tests of the chemistry in selected samples extracted from the stored items. Another possibility would be to monitor the stabilizer content directly, using embedded sensors, or indirectly, by monitoring stress in shell surfaces or pressure build-up in enclosed compartments.

4.3 Techniques for life cycle evaluation

IM properties are important not only during military operations, but should be considered in the munitions entire life cycle, including manufacture, storage, transport, and operative usage on a military platform, as well as discarding and demilitarization. Other factors than the IM signature may be included in a life cycle evaluation, for example operative performance, environmental impact in all stages of its life cycle, as well as the total cost for a complete munitions system.

An outline for a whole life-time study of munitions is given by de Klerk et al. [32], who identify the following phases:

Phase 1: Define environment and identify all failure mechanisms

Phase 2: Identify potential life limiting failure modes

Phase 3: Determine assessment techniques to be used

Phase 4: Modelling and monitoring

Phase 5: Determine life for which munition remains safe and serviceable

One way of performing a quantitative Threat Hazard Assessment (THA) for the entire life cycle of IM is given by Graham and Spear [33]. A total risk probability is obtained by dividing the life cycle into steps (storage, truck transport, mil transport, operational use, etc.) and assigning a probability for each identified threat to occur in that life cycle step. Utilizing a frequency and damage severity risk matrix, quantitative measures of system risks can be obtained and the primary contributors to the system risk identified. The method may be used as a design tool to evaluate and compare risks of various designs.

A similar approach is given by de Klerk et al. [32] as a Function-Failure-Analysis (FFA), where a number of critical 'sub-functions' are evaluated. When the expected conditions during the lifetime of the munitions item have been identified, the influence on the ageing processes of the sub-functions is estimated. For every sub-function the risk of malfunctioning is determined as a function of storage time:

$$\mathrm{RISK}(t) = \mathrm{CHANCE}(t) \cdot \mathrm{SEVERITY}(t),$$

The risk increases with age, while the service lifetime is determined by the sub-function with the highest risk.

However, as pointed out by MacKichan et al. [7] the IM assessment process "… neither attempts to measure the probability of inadvertent initiation nor does it measure collateral damage", but "… information from IM assessment can provide a key input to the subsequent risk-based munition safety assessment".

Two examples of systems approach applied to life cycle survivability improvement are given by Sotsky et al. [34], for a 120mm M934A1 High Explosive (HE) Mortar Cartridge, and Niles et al. [35], for munition to an XM155 Spider grenade launcher.

As pointed out by the Insensitive Munitions European Manufacturers Group (IMEMG), the life cycles of munition can differ from one nation to another and from one user to another [25]. Similarities and differences between national positions in France, Germany, UK, and US regarding IM practices are given in the document MSIAC L-147 [36]. It should also be noted that there are differences between different nations in the definitions of criteria for IM classification [37], see Table 3.

A guide for the assessment of the safety and suitability of non-nuclear munition for use by NATO forces with recommended system safety design and development criteria for munition systems, subsystems, and components is given in AOP-15 [38]. The severity of incidents is classified as *Catastrophic*, *Critical*, *Marginal* or *Negligible*, while the probability for incidents are classified as *Frequent*, *Probable*, *Occasional*, *Remote*, *Improbable* or *Extremely Improbable*. The risk level assessment is then handled in a Risk Level Matrix.

Table 3. Differences in definitions of IM-criteria. To be classified as IM the reaction level is not allowed to be lower than the level given in this table for the different test procedures [37].

Test procedure	**France**			**NATO**	**UK**	**USA**
	DGA MURAT			**STANAG 4439**	**STANAG 4439**	**MIL-STD 2105C**
	*****	******	*******			
Fast cook-off	IV	V	V	V	V	V
Slow cook-off	III	V	V	V	V	V
Bullet impact	III	III	V	V	V	V
Sympathetic detonation	III	III	IV	III	III	III
Fragment impact (light)		III	V	V	V	V
Fragment impact (heavy)		III	IV	V		
Shaped charge attack			III	III	III	III
Spall impact				V	V	V
Drop	NR[1]	NR[1]	NR[1]	NR[1]	NR[1]	NR[1]
Electrostatic discharge	NR[1]	NR[1]	NR[1]			

[1] NR= no reaction

Harmonization is especially pertinent today, with many nations participating in international peace keeping operations in climatic zones for which the existing equipment was not originally designed. Interoperability requirements in international peacekeeping operations constitute a strong incentive for establishing harmonised IM requirements and operational procedures. Much work on harmonization with respect to insensitive munitions is performed in organisations such as IMEMG [25,39].

5 Conclusions

The fundamental question “Is the IM signature changing with ageing of a particular munitions system and how can the progress of ageing be determined?” is complex and requires an extensive test program.

There are several different ageing processes, chemical, physical and mechanical, each with its own test procedure and assessment methods. Since many newly developed materials, both energetic and non-energetic, are used in IM systems, there is a vast need for efficient methods for investigating stability and compatibility, as well as progressive changes in performance and in IM properties.

In addition to testing munition samples at discrete intervals and testing samples exposed to accelerated ageing, continuous monitoring of key properties in storage may also be needed. Since the ageing processes depend on a number of environment factors, such as temperature, humidity, vibration, radiation etc., ageing and its effects on the IM signature depends on the entire life cycle of the munition. Hence, transfer of existing munitions and weapons system to new environments may adversely affect the performance and IM signature and lead to unexpected accidents if these problems have not been properly addressed in advance.

Furthermore, there are new kinds of threats, such as IEMI, Thermobaric warheads and IEDs, which need elaborated standards and tests for ageing and IM signature impact.

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