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Insensitive Munitions (IM): A Key Aspect of Improved Munitions Safety

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Abstract: The development of Insensitive Munitions (IM) has been progressing for over three decades. Ever since the highly publicized US Navy aircraft carrier accidents in the 1960s to 1980s, there has been a growing recognition of the value of IM. Reminders of the need for IM have been provided all too often in the form of accidents, such as experienced by the US Army at Camp Doha and the prevalence of attacks on military installations around the world.

The process for developing IM has improved over the years as technology for mitigating the consequences of accidental initiation has emerged. Early IM developments were based upon replacement of the traditional TNT-based explosives, with their high vulnerability, with reduced vulnerability PBXs. This led to significant improvements, such as that observed with the replacement of H-6 with PBXN-109 in the US Navy Mk82 GP bomb. From the early 1990s, the use of a complete systems approach was highlighted as the optimum method to achieve IM compliance while maintaining or enhancing operational performance. The use of a systems approach has resulted in the fielding of a number of munition systems with significant IM properties.

The challenge for the future is to continue the development and fielding of improved performance IM munitions with limited funding for research and the high cost of introducing new ingredients into energetic formulations.

A key development to allow continued progress to occur is the introduction of improved versions of current explosive ingredients. The attention focused in the past few years on forms of RDX with reduced shock sensitivity has highlighted the possibility of improving well-known materials. In the near future, the application of materials technology may provide improved versions of other important crystalline energetic materials currently in production or advanced development, including HMX, NTO, CL-20 and ADN and help advance the development of further explosive ingredients such as FOX-7 and LLM-105.

Advances in the development and application of computer modeling must be made if we are to move forward from our current reliance on a limited number of canonical tests that are held to be representative of the hazards likely to be encountered. The availability of verified and validated models describing the response of energetic materials to various thermal and mechanical threats will enable us to perform parametric studies on systems. This will allow us to estimate their response to hazards that are characteristic of the specific environment experienced by that system, and so to tailor the materials and packaging to minimize risk and maximize performance.

Key words: Insensitive Munitions (IM); safety; material science; crystalline; computer simulation

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1　Introduction

The development and fielding of Insensitive Munitions (IM) has been occurring over the last 30+ years. The high profile accidents on the USN aircraft carriers Oriskany, Forrestal and Enterprise spurred the US Navy to action. The toll that these accidents took in terms of loss of human life, and loss of platforms, impressed upon the Navy the critical importance of taking into account not only the performance of munitions but also their vulnerability to accidental initiation. However, the requirement for performance was not subsidiary to the requirement for insensitivity, and there was concern in the early days of IM that it might not be possible to achieve insensitivity, desirable though it might be, without sacrificing performance.

Since these historic aircraft carrier accidents, further events have underscored need for munitions offering reduced vulnerability. One of the most publicized and studied event is the Camp Doha accident during the 1991 Gulf War[1]. The basic sequence of events for this accident was:

(1) ‘minor’ electrical fault in a heating unit in a Field Artillery Ammunition Supply Vehicle.

(2) This electrical malfunction caused a hydraulic fire.

(3) This fire gave rise to an explosion of gun pro-

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pellant charges in the vehicle.

(4) This explosion and fire then propagated to surrounding vehicles.

(5) Fire and explosions continued to spread and build for many hours.

(6) Final damage caused was 3 killed, 56 injured, 84 vehicles destroyed including M1A1 battle tanks, 77 vehicles damaged and an environmental clean-up including DU tank ammunition.

The wide spread usage of Insensitive Munitions, which are designed not to propagate explosive events, would have significantly reduced the consequences of this event sequence. Fig. 1 provides a summary of the reported consequences of the event and an analysis of the consequences if solely insensitive munitions were involved.

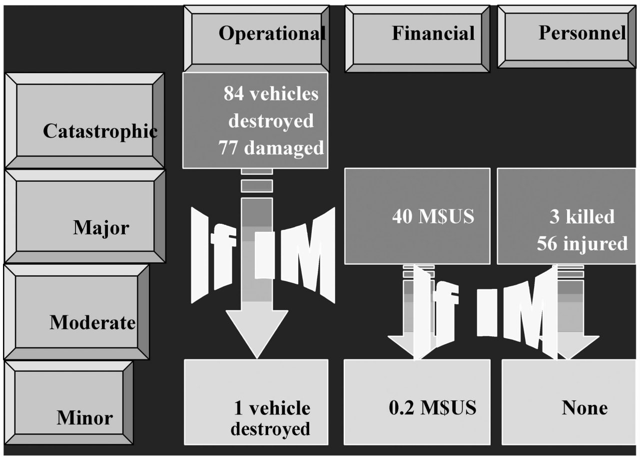


Fig. 1 Calculated reduction in consequences from Camp Doha accident if Insensitive Munitions were exclusively deployed

Insensitive Munitions (IM) can be defined as those munitions which reliably fulfill performance, readiness and operational requirements on demand, but minimize the probability of inadvertent initiation and severity of subsequent collateral damage to the weapon platform logistic systems and personnel when subjected to unintentional stimuli[2]. The requirements for IM are shown in Table 1.

In simple terms, IM are munitions which: (1) Burn when subjected to fast cook-off (FCO), slow cook-off (SCO), bullet impact (BI) or fragment impact (FI); (2) Do not detonate when subjected to shape charge jet impact (SCJI) or when another munition detonates in a stack (Sympathetic reaction, SR).

2 Hazard Classification of IM

One of the principal operational benefits associated with the introduction of IM in service is the potential for improved logistics and deployment opportunities, particularly in terms of reduced real estate requirements and the ability to establish camps and munitions storage operations in areas that previously would have been unavailable due to quantity distance (QD) issues/violations. This is because conventional munitions that are hazard classified as United Nations (UN) Hazard Division (HD) 1.1 have their operations very tightly restricted by QD relationships. Significant safety arcs, and the ever-present danger of sympathetic reaction, mean that the logistic footprint associated with HD 1.1 munitions is very large.

In the best-case scenario, IM would be assigned to UN HD 1.6 (where all contained explosive substances have passed specific UN tests to be considered Extremely Insensitive Detonating Substances (EIDS)). HD 1.6 items are defined as "Extremely Insensitive Articles which do not have a mass explosion hazard"[3]. For such munitions, there is a negligible risk of accidental initiation of a round, and no risk of sympathetic reaction of acceptor rounds, and so the precautions required to protect personnel, material and facilities from the consequences of accidental initiation are much less.

However, a UN HD 1.6 classification is very difficult to attain and is seen as more a long-term goal for most IM development programs. So, in the near term, and in order to benefit from the incremental improvements in IM development, Storage sub-Division (SsD) 1.2.3 has been developed for application to the storage of munitions that have met certain IM test requirements. A number of Nations and NATO have criteria that allow the use of the SsD 1.2.3 classification for munitions storage and provide reduced safety distances for it. In order to be considered as SsD 1.2.3, a munition item must first qualify as UN HD 1.2 and then must meet certain worst-reaction limits described in NATO Stanag 4439 for 4 NATO IM tests (i.e., BI, FCO, SCO, and SR) as outlined, respectively, in NATO STANAGS 4241, 4240, 4382 and 4396).

The paper by Deschambault provides a thorough review of the relationship between IM classification and testing and UN/NATO transport and storage hazard classification criteria[4].

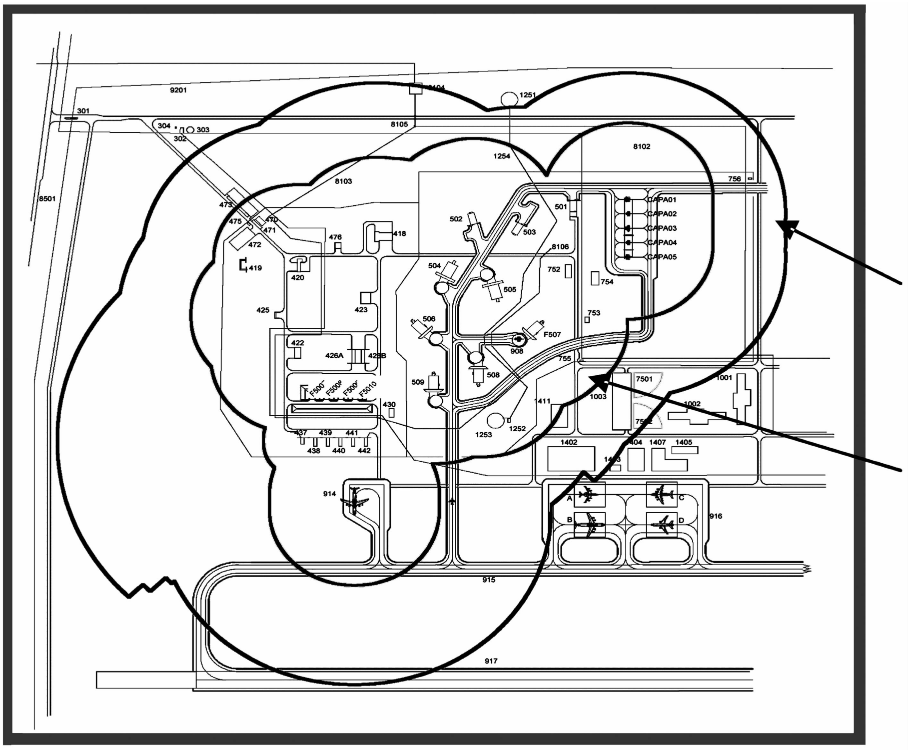
Other Nations have established their own criteria (other than SsD 1.2.3) to take advantage of incremental improvements in IM programs. For example, France has developed a MURAT*, ** and *** designation system, while Italy has a MURAT$^{\Phi}$, $^{\Phi\Phi}$ and $^{\Phi\Phi\Phi}$ designation system for IM compliance levels. Be aware that these classifications don't necessarily represent the same levels of IMness. Some comparisons of the UN, NATO and other National IM classification are provided in Table 1.

As a comparison of the impact of having non-IM versus IM on QD, Figure 2 illustrates the effect, on the logistics footprint at a notional airbase, of changing the entire munitions inventory from HD 1.1 to SsD 1.2.3. As can be seen, a huge increase in storage capacity and/or reduction in footprint can be achieved. The transition of the entire inventory to HD 1.6 would have a further effect [5].

Table 1　Comparison of hazard division for storage/transport and IM criteria

STANAG 4439 tests[1)]	UN HD 1.2	UN HD 1.6	NATO NATO IM[3)]	FR MURAT*	FR MURAT**	US SsD 1.2.3	NATO NATO SsD 1.2.3	UN tests
SR	I or II[2)] (<50%)	III	III	III	III	III	III	6(a), 6(b) or 7(k)
FCO	IV	V	V	IV	V	V	V	6(c) or 7(g)
SCO	NA	V	V	III	V	V	V	7(h)
BI	NA	III	V	III	III	V	V	7(j)
FI	NAV	NA	III	NA	NA	NA		
SCJI	NAIII	NA	NA	NA	NA	NA		
UN EIDS requirements on energetic material								
no	no	yes	no	no	no	no	no	EIDS tests

Note: 1) Reaction Levels: Type I = Detonation, Type II = Partial Detonation, Type III = Explosion, Type IV = Deflagration, Type V = Burning; 2) Partial detonation (II) of the acceptor or < 50% (type I) of munitions detonate inside the logistic container; 3) STANAG-4439 requirements for Insensitive Munitions.



- All Facilities Sited for Maximum Capability for both HD 1.1 and SsD 1.2.3 storage-No QD violations
- HD 1.1-base can have max. ~500T ordnance-clear zone = ~520 acres
- SsD 1.2.3-base can have max ~3,000T ordnance, clear zone = ~250acres
- SsD 1.2.3 calculated to provide a 500% increase in available ordnance in < half of land area

Fig. 2　Analysis of HD 1.1 and SsD 1.2.3 siting at an airbase ordnance storage location

3　IM Success Stories

The development of munitions designed to fulfill the requirements of IM has rapidly increased over the last decade. MSIAC has developed and has available the IM State-of-the-Art, which provides details on more than 35 in-service systems that offer IM properties with maintained or enhanced performance. The paper by Swierk, T. (2006) provides a summary of the improvements that have been achieved in the development of Insensitive Munitions over the last decades from a USN perspective[6]. Among those readily identifiable include the US Army 60mm M720E1, USAF AGM-84 SLAM-ER, French Navy CBEMS/BANG 125, US NAVY AGM-158 JASSM, Joint ESSM, UK Storm Shadow, French Army LU-211 155mm HE and the MU-90 LW torpedo, to name but a few.

A very advanced IM example is the French Navy CBEMS 250 multipurpose bomb, see Figure 3 which is reproduced with permission from M. Bruno Nouguez, CBEMS Program Manager, EURENCO. This munition was specifically designed for carriage onboard the Charles de Gaulle aircraft carrier. It is an important example of the reduction in hazard classification that can be obtained even in large munition items. The MBDA/SME designed munition allowed the attainment of a HD 1.2 unit risk hazard division, it was also awarded a "MURAT** IM rating" by the French DGA. The IM signature was obtained through a combination of:

(1) The NTO-based cast PBX B2214B - an EIDS as the main charge.

(2) An embedded ORA86A booster to provide reliable initiation at all operational temperatures - not EIDS.

(3) Internal liner to provide thermal and mechanical insulation and control fragmentation.

(4) Venting system in the aft closure plate.

(5) Logistic pallet with the 'diagonal effect' avoided by geometric design.

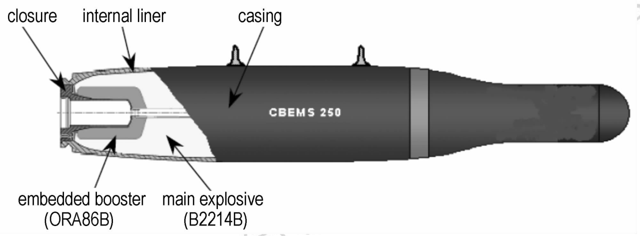


Fig. 3 Schematic of the design of the CBEMS 250 IM Multipurpose Bomb

4 The Role of Materials Science

The systems approach to development of IM utilizes all of the methods and ingredients that are available for achieving IM including mitigation systems, packaging, venting and initiation design. The use of reduced vulnerability energetic materials is still a cornerstone in the attainment of IM.

The process required to discover, scale-up and apply completely new energetic material for use in a munition system is a long, involved and expensive process. The development and exploitation of CL-20 has perhaps occurred over the shortest period (outside that encountered during the World Wars). The first molecules of CL-20 were synthesized in 1987, 17 years ago, but it is still a developmental material. Part of the reason for this is related to economics (new compounds are always expensive until there is a market for large quantities, at which time the price may come done significantly). A larger part of the explanation is that the high performance of CL-20 is coupled to relatively high level of sensitivity. Until the sensitivity could be moderated to an acceptable level, the hazards associated with its use outweighed the benefits of its higher energy.

While the exploitation of new energetic materials is a long process, the application of state-of-the-art materials science can help us to overcome the barriers to the use of some known materials, to improve the properties of materials currently in use, and to overcome some of the difficulties associated with new materials as they are discovered. Several compounds, that have been known for many years and have good performance and sensitivity properties, are not used because they have not been obtained in a particle size and/or morphology that lends itself to facile processing[7].

Applied research, with the eventual limitations and constraints applicable to the manufacturing environment kept in mind, will offer the potential for faster transition from the lab-bench to manufacturing and the munition system. A complete understanding of the crystallization process will lead to the production of more desirable morphologies and less flawed/more perfect crystals promises to improve the energetic materials available for IM.

4.1 RS-RDX

The recognition and application of reduced sensitivity RDX (RS-RDX) is the most recognizable achievement in materials science being applied to explosive crystal properties. The potential for the existence of RS-RDX was highlighted by SME during the late 1990s. Since this time, much interest and research has been devoted to development and exploitation of the material, and other less widely publicized but previously known versions of RDX have also been offered as examples of RS-RDX. At present, four manufacturers are offering materials with claims to be variants of RS-RDX. The SME/Eurenco version of RS-RDX, i-RDX®, is used in the in-service formulations HBU-88A and B2213A, and the material has been considered for numerous other systems, including the US Army 120mm mortar program.

The development of RS-RDX is now at such a stage as to warrant the development of a NATO STANAG to allow specification of the material. The article by Doherty et al[8] provides up-to-date details of the progress of this activity.

4.2 RS-HMX

Application of the improved processes used for RS-RDX development is being considered for HMX[9,10,11]. It has been reported that a strong correlation exists between the sensitivity of HMX-based PBX formulations and the intra-crystalline voids present; research has been reported by, amongst others, ICT, ISL, and TNO. Both SME and Dyno are also actively developing industrial processes to allow for the production of reduced sensitivity HMX. The extent to which this approach can reduce the shock sensitivity of HMX is not clear, since a direct analogy with RDX is prevented by, among other things, the difference in solubility's of the two compounds, the different space groups in which they crystallize, and the propensity for twinning in HMX that is absent in RDX. Fig. 4[12] provides an example of the decrease in shock sensitivity possible through using 'reduced-sensitivity' nitramines.

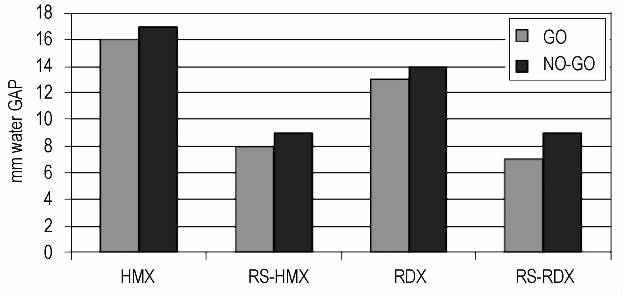


Fig.4　Comparing HMX and RDX in a PBXN-109 composition and tested with the BICT gap test-nominal nitramine content = 60%

4.3 CL-20/ADN/HNF

Lessons learned in the development of reduced sensitivity RDX and HMX provide the opportunity for significant improvements in the sensitivity of explosive formulations. The use of newer energetic materials will provide the opportunity for an incremental performance improvement, along with potential vulnerability gains. While the same principles that have been applied to achieve better shock sensitivity properties in RDX appear to be relevant also to CL-20[13], shock sensitivity is not the only facet of insensitivity that must be addressed in order to achieve IM. Some new materials have issues with thermal, hydrolytic, photolytic, or other instabilities that may limit the uses to which they may be put.

Both ADN and HNF offer potential for use as high-energy density oxidizers for composite rocket propellants. The successful use of both materials is dependent, among other things, upon optimization of the crystal morphology. Eurenco Bofors and ATK/Thiokol have worked together to develop the process to prill and incorporate stabilizer (e.g. hexamine) and hydrophobic anti-caking agent (e.g. DOS) into prilled ADN. The ability to consistently produce spherical, high stability and density ADN should enhance the possibility to exploit the chemical potential of the material.

The successful optimization of HNF crystal morphology, including use of co-crystallization techniques allowing the incorporation of stabilizers and/or ballistic modifiers, will be essential if this material is to be utilized in propellant systems.

4.4 NTO

NTO is currently in service in select munitions as a component in PBX systems, such as B2214B used in the CBEMS described above, and melt-cast explosives, e.g. XF-13153/333 used in the LU-211 155mm MURAT*. The potential for application of NTO in melt-cast systems will be significantly enhanced when progress is made in crystal morphology, to minimize viscosity and allow for higher solids loading. The crystallization of NTO, unlike that of most other commonly used energetic compounds, is possible in an aqueous matrix. Without effective control of crystallization procedures undesirable crystal structures, such as particles containing numerous defects, or platelet structures, result and high viscosity at relatively low solids loading is observed during processing. Research into crystallization techniques that provide for improved crystal morphology is underway with significant potential for improvements already reported[14].

5 Vulnerability Compositions

With the application of reduced vulnerability energetic materials and formulations considerable strain can be placed upon the reliability of the initiation systems. In order to maintain reliability of ignition with these low vulnerability, potentially high critical diameter compositions, it is essential to validate the booster material, geometry and uptake. In order to allow HD 1.6 to be achieved across the entire range of munitions, fundamentally different ways to initiate them may be required.

Among the advances that will enable munitions of the future to achieve IM compliance, the strides in computational capability will be one of the most important. In the absence of physically faithful models of the initiation and growth of reaction in energetic materials, munition designers are constrained to build safety margins into their designs and to select materials that are well within the boundaries of what might be considered a safe regime to prevent accidental initiation. Success is determined by the response of a munition to a limited number of hazard tests (slow and fast cook-off, bullet impact, fragment impact, shaped charge jet impact, and sympathetic detonation), which may or may not reflect accurately the actual hazards likely to be encountered by the munition during its service life. The availability of ever-faster and more capable computers, coupled with computer models that capture more of the actual phenomenology of the energetic materials under accident conditions, will permit wide-ranging parametric studies to be done to assess hazards in systems that are too large or too expensive to test in full-scale.

Computer modeling has been successfully applied to the task of optimizing booster design for given explosive composition. At times, the shape of the booster can be optimized to provide required shock strength and duration, in some situations however it is essential that imbedded boosters are utilized. The use of ultra fine, and nanomaterials (with DDT mechanisms different from those of conventional particle size materials) and prevalence of non-ideal high-metal content compositions both increase the complexity of the explosive-train design.

Although current models of initiation by a sharp shock are fairly well developed, our understanding of the role of shear and combined shock and shear is not as far along. Since most accident scenarios involving mechanical initiation include some component of shear, our ability to predict the outcome in a configuration that has not been tested will depend on our ability to capture the appropriate phenomenology in our models.

6 Future Developments of IM and Materials Technology

It is likely that there will remain, at least in the foreseeable future, the need for the "Admiral's Test" in munition design. However, with the ever-increasing availability of computational power, the use of modeling to simulate the effect of various stimuli upon the explosive compositions without having to test every environment or threat must increase. It is often difficult to persuade users that investment in modeling is cost-effective: it takes so long to develop good, verified, validated models that are usable by someone other than the developer, that it is more expeditious to simply go out and test a few items to determine how they behave.

This line of reasoning overlooks the fundamental nature of accidents and the economic impossibility of doing enough tests to have a statistically valid basis for a statement about the relative hazards of one munition or another subjected to one threat or another. The reliance on a limited number of tests is even more speculative when one takes into account the primitive nature of our understanding of the aging of those materials that have made it possible for us to achieve the levels of insensitivity and reduced hazards that we enjoy today. While we may have some level of confidence that new munitions have low vulnerability toward unplanned initiation, that confidence is much lower for real-life munitions for which the environmental history is unknown. Advances in safety must be accompanied by advances in our fundamental understanding of munitions, and the energetic materials within those munitions, as a function of the ageing process.

7 Summary

Insensitive Munitions have come of age in the new millennium. Technology is now available, in fielded systems, which allows for the improvement in IM response of almost any munition type or system. The ultimate goal of attaining UN HD1.6 still requires more research and development activity, particularly to allow the mitigation of the threat of shaped charge jet impact. The use of new materials, better materials science and enhanced computational efforts will provide the opportunity for incremental advances in munition safety along with fulfilling the ever-increasing demand for higher performance.

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读者·作者·编者

第九届全国爆炸与安全技术学术会议召开

由中国兵工学会爆炸与安全技术专业委员会、东北大学、北京理工大学爆炸灾害预防控制国家重点实验室主办的第九届全国爆炸与安全技术学术会议于 2006 年 9 月 22 日～24 日在沈阳召开。来自航天集团的一院和四院，中科大、国防科大、北理工、南理工、中国矿业、中国石油、中北等大学，中国工程物理研究院、西北核技术、兵器 213 所、204 所等研究机构约 60 位专家学者参加了会议。会议约收到论文 70 篇。

会上，中国兵工学会爆炸与安全技术专业委员会主任委员冯顺山教授、煤炭科学研究总院重庆分院张延松教授、南阳防爆电气研究所王云生教授等 10 位专家分别作了《高价值设施的终端防卫——近程/超近程反导途径研究》、《气体粉尘爆炸的研究与应用》、《我国防爆电气产品的现状及发展趋势》等大会报告，并有 28 人进行了分组报告。

这次学术会议突出了工业粉尘爆炸防护技术和爆炸安全控制技术成果交流，在爆炸过程数值计算方面呈现出百家争鸣景象，达到了学术上沟通、交流、共享的效果。

（中国工程物理研究院化工材料研究所 左军供稿）