TRANSLATING THE IM BEHAVIOUR OF MUNITIONS TO OPERATIONAL CONSEQUENCES

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Abstract
A recent study was dedicated to relate the behaviour of Insensitive Munitions (IM) to an operational context. At TNO, a toolbox with a series of engineering tools is under study. These tools focus on the mechanisms that occur due to a range of IM threats and that transfer the effects from a reacting (donor) munition article to the neighbouring (acceptor) munition articles, focusing on sympathetic reaction. The consequences of this mechanism could be devastating, resulting in a mass detonation of large quantities of munition in storage on a compound, aboard a ship or in a vehicle. However, by using Insensitive Munitions and mitigating structures these effects and their operational consequences could be limited.
In order to quantify this limiting effect and the consequences of such an event in an operational context, a case study has been performed on an Out of Area compound. Attention is given to the effects and consequences of a detonation of an munition storage facility on the war fighters and infrastructure on the compound in terms of probability of injury and damage. At a higher systems level a translation is made to the Essential Operational Capabilities of the compound.
This evaluation puts the benefits of Insensitive Munitions and mitigating measures in the right perspective and challenges research institutes in finding new solutions in Insensitive Munitions technology.

Introduction
Within the research program 'Protection and Survivability of compounds' the NLD MoD has asked TNO to develop a cost-benefit analysis methodology for compound protection against a variety of threats. For this purpose the effects and consequences of these threats for resources at the compound have been assessed. The consequences are, amongst others, measured in terms of injury and lethality of the compound population, and damage to infrastructure [1].
A specific case study in this program focused on the effects and consequences of a mass detonation in a compound environment. This scenario could take place due to an accident, or due to an impacting mortar or Rocket Propelled Grenade (RPG). Although the probability of such an event is rather small (if appropriate counter measures are taken) the consequences could be devastating. This study allowed for an evaluation of the benefits of the use of Insensitive Munitions by comparing the consequences of a mass detonation with the consequences of detonation of a limited amount of ammunition.

This paper first addresses the results of the above mentioned case study. Then, the activities of TNO concerning a sympathetic reaction Toolbox are discussed. This more detailed and in depth discussion will focus on a series of engineering tools under study to assess the effects from a detonating donor article that result in the occurrence of a sympathetic detonation. Based on the outcome of the engineering tools, mitigating measures can be taken to protect the munition storage from progressing from a minor event to a mass detonation. This paper presents the present status of this ongoing work.

Case study: Mortar attack at a compound
The virtual compound used in the case study lies in a valley between two mountain ridges and houses about 250 men. The compound has in good approximation a circular shape with a radius of about 240 m. The compound and its surroundings are schematically shown in Figure 1.
The operational commander of a compound can take both passive and active countermeasures against mortar attacks. The passive measures are related to physical protection such as enhanced container design, placement of barriers, or protective clothing for military personnel. Active measures can be established by creating Situational Awareness (SA) with camera systems and other sensors, in combination with, for example, a Quick Reaction force.

In the current paper we focus on the possible follow up scenario of a detonation in the ammunition storage after a mortar attack.

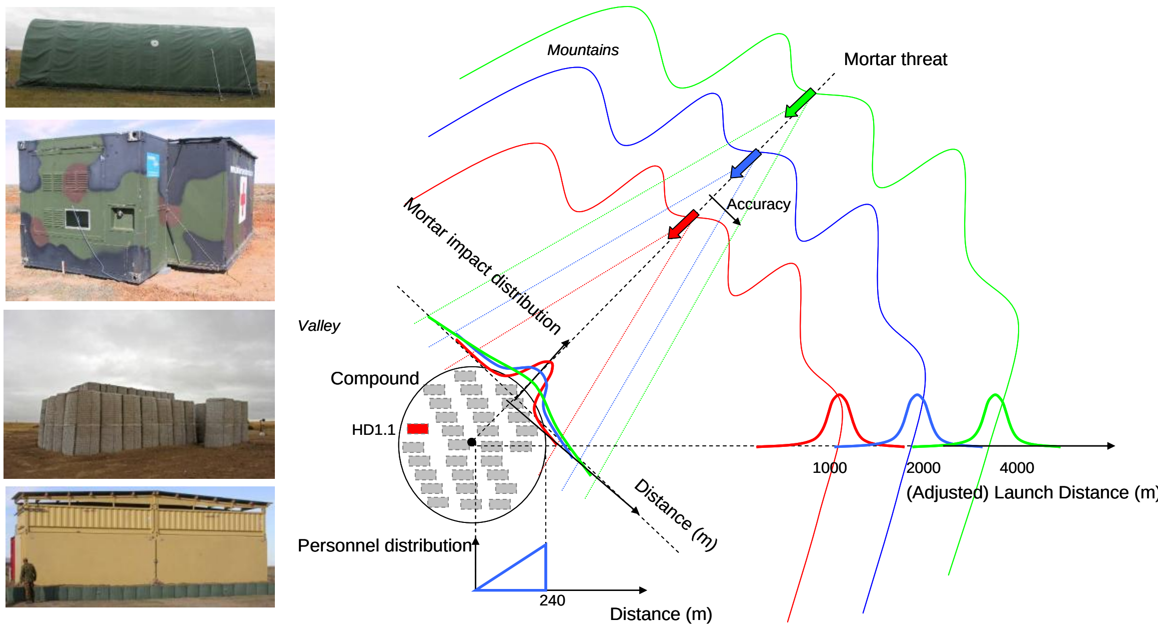

Figure 1 Set up of a virtual compound for the case study (right) with a variety of structures (left).

Figure 2 Test at TNO with mitigating materials placed between donor and acceptor shells [2].

Detonation of the ammunition storage

To calculate injury, lethality and damage in a mathematically correct fashion the Bayesian Belief Network (BBN) technique has been adopted. A Bayesian belief network is a probabilistic graphical model (a type of statistical model) that represents a set of random variables and their conditional dependencies. With this technique, for example, variations of the launch distance, accuracy, mortar type and mortar impact location can be combined.

Based on the analysis results for the consequences of a 4000 kg detonation, the probability of injury and lethality are calculated and displayed in Figure 3 for personnel inside a large variety of structure types on the compound. Especially the consequences for personnel in ‘light’ structures or in ‘normal (ISO container)’ structures with windows are enormous. This is caused by the strong blast wave which dominates the injury and lethality in case of the 4000 kg mass detonation due to failure of the structure and its windows. The consequences are smaller for personnel in tents and in the free field. In these cases fragments are dominant.

As expected, the probability of lethality for this event is generally much larger as compared to the situation in which only a limited amount of ammunition of 56 kg TNT equivalent detonates, see Figure 4. Note that 56 kg is equal to the net explosive weight of a single pallet of artillery shells.

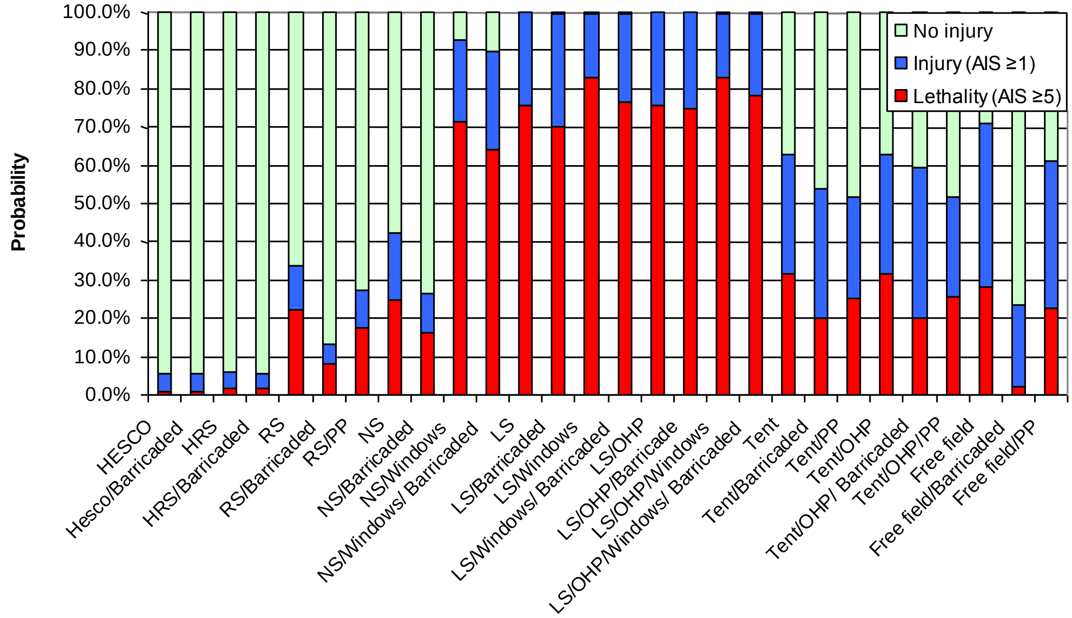

Figure 3 Probability injury and lethality for personnel in various structure types (4000 kg TNT equivalency). LS = Light Structure, NS = Normal(ISO) Structure, RS = Reinforced Structure, HRS = Heavily Reinforced Structure, PP = personal protection.

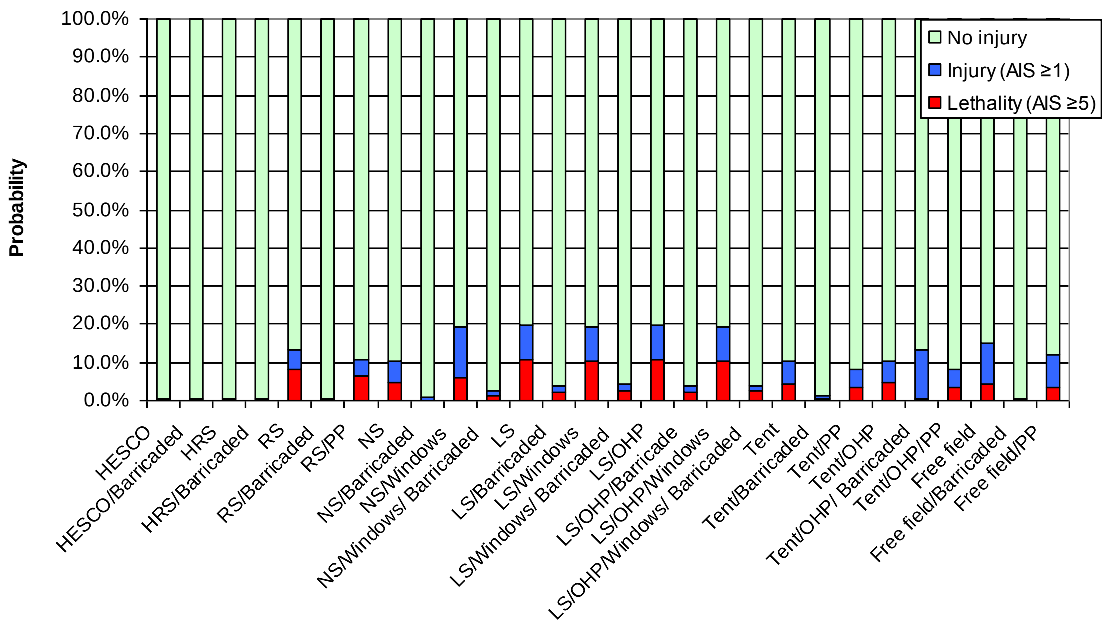

Figure 4 Probability of injury and lethality for personnel in various structure types (56 kg TNT equivalency). Abbreviations are as in Figure 3.

The difference between both situations is clear and is an excellent illustration of the importance of being capable of reducing the occurrence of sympathetic reaction. It illustrates the importance of technological improvements in the field of Insensitive Munitions and mitigation technology. Often, the attention is given solely to innovations in the field of insensitive energetic materials, venting solutions or more system-related innovations involving packaging of munitions. But, the above evaluation sets the stage for all this innovative work and should motivate and challenge researches in their activities, which, in the end, are being performed to protect the war fighter in an inherent/intrinsic dangerous environment.

Outline Sympathetic detonation Toolbox

In 2009, a 4 year project was started entitled 'Safe storage of munitions and safety-increasing measures'. The main goal in this project is to set up an engineering toolbox for evaluating the behaviour of munition in storage. Within the limitations of the project the effects of a detonating donor on neighbouring munition is investigated (1) experimentally, (2) by the evaluation and development of engineering tools and (3) by numerical simulation.

The process that is followed in the Toolbox is captured in the flowchart below (Figure 5). The flowchart represents three parts, shown from left to right: Threat – Donor – Acceptor.
The event starts off with an external threat on a munition article. This external threat acts on the donor, causing a range of possible effects. The effects are checked in a logical manner, using data describing characteristic data of the projectile (shape, velocity, mass, material) and data of the munition article involved (casing material and thickness, explosive fill, angle of attack). As is seen from the flow chart subsequentially Shock to Detonation Transition (SDT), penetration of the donor casing and deformation of the donor article are evaluated. Based on the outcome of these checks, additional checks have to be made resulting in either the conclusion that the donor will detonate under influence of the external threat, or the process is stopped, because the flow chart leads to the conclusion that no detonation of the donor is found (Note, until now less severe reactions of the donor are not covered by the Toolbox).

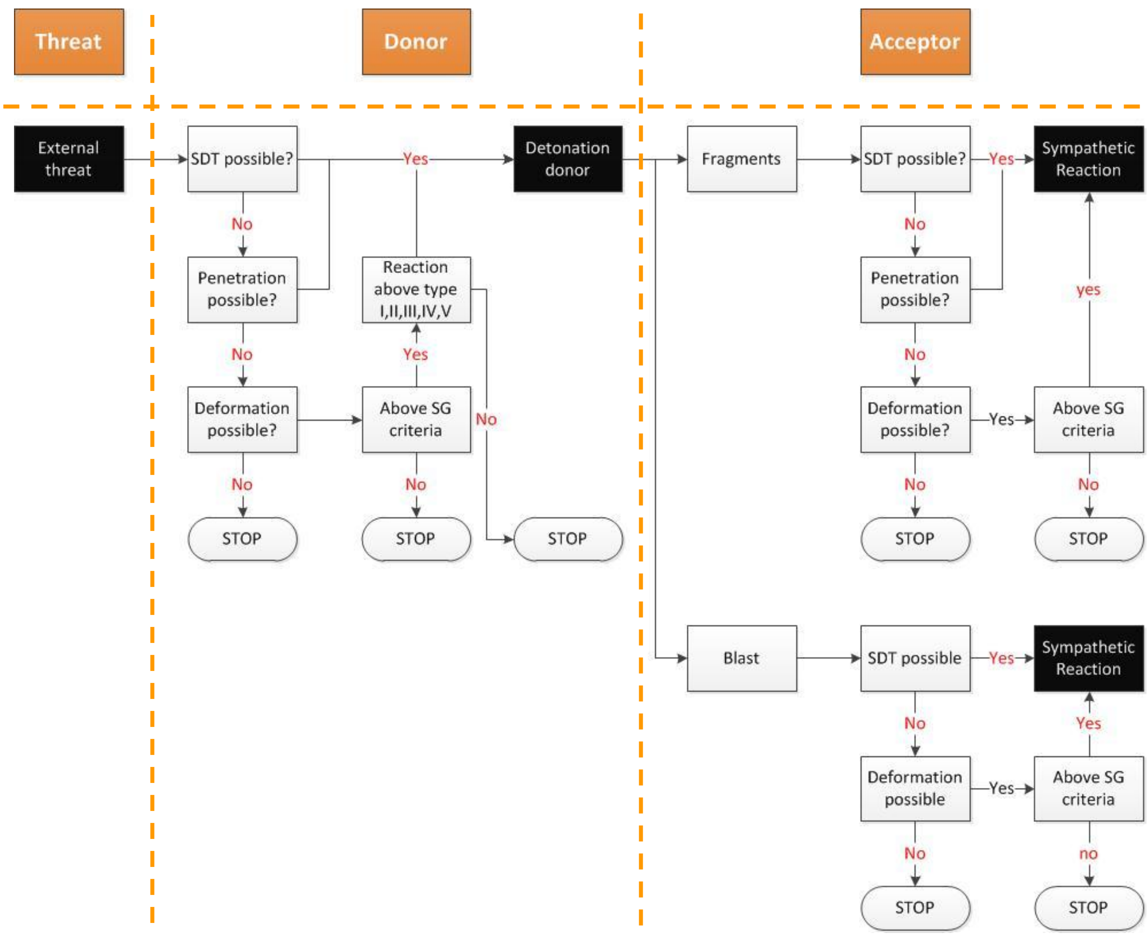

Figure 5 Flow chart showing the procedure covered by the sympathetic Reaction Toolbox.

The sub-procedure under the 'Donor' part evaluates when a munition article is deformed, the loading results in surpassing the Sensitivity Group criteria for that specific munition item. This check is based on an evaluation done for the so-called High Performance Magazines (HPM) [3].

When the donor detonates, the effects of this donor on neighbouring munition is evaluated, based on the characteristics of the donor article (dimensions, materials). For each of the effects the same procedure is followed as for the evaluation of the external threat on the donor article: Is SDT possible? Is penetration possible? Is deformation possible? And again, based on the outcome, either the procedure is stopped or leads to the conclusion that a sympathetic reaction is to be expected and a barrier is required to prevent this.

Engineering tools

A range of engineering tools is being used in the Toolbox. For all of these tools the intention has been to use tools that can be implemented in Microsoft Excel, such that the tools can be used on regular desktop computers. A second positive aspect of implementing these tools in such a common software is that, once the relevant input data are known, the evaluation can be done quickly and variations, based on the actual storage of the munitions articles (like mutual distance, or variation of munitions types), is relatively simple.

The following Table 1 gives a schematic overview of the models that are implemented in the Toolbox in the way as described by the flow chart. The models either have been taken directly from literature, or have been modified by TNO for improved accuracy or have been fully set up by TNO. The table indicates the relevant references for each of the models. A source to be separately mentioned is the Victor Technology sheets for sympathetic reactions [4] which provides a range of spreadsheets in which part of the models are covered. These spreadsheets have been taken as a basis for some of the models implemented and are currently under investigation for verification and/or improvement.

Table 1 Condensed overview of the engineering tools used in the Toolbox.

Model	Description/Principle	Reference
Shock to Detonation	Shock Hugoniots, Critical Energy Criterion (Walker & Wasley), Influence casing (Haskins & Cook), optimization by TNO	Victor [4], Bouma [5], Scholtes [6]
Penetration casing	THOR code empirical model for the penetration of materials	Victor [4], Scholtes [7]
Penetration Explosive fill	THOR code and low speed charge penetration; shear loading of charge (Frey, Sewell and Graham)	Victor [4], Scholtes [7]
Cook-off after penetration	Cook-off analysis (Scholtes)	Scholtes [7]
Burning to DDT	After ignition: burning, which pressure increase vs. venting	Victor [4], Scholtes [7]
Deformation	Flyer plate testing, Sensitivity group criteria for munition in High Performance Magazines	Murtha [5]
Sympathetic reaction (deformation)	Increasing area of impacting casing	Victor [4]
Fragmentation	Mott fragmentation of rings en shells	Mott [8]
Blast	Kingery and Bullmash. Updated by TNO for small distances	Kingery, Bullmash [9], Verbeek [10]
Muntion schematisation	Munition article is converted to cylindrical shaped item	Crull, Swisdak [11]

Case study: Mortar attack at a munition storage

It would be too detailed to cover all details of the models used in the flow chart to be discussed in the present paper. Therefore, its use is demonstrated by taking the case study as mentioned in the first part of the paper in which a mortar attack on a compound threatens a bulk storage of 155 mm M107 projectiles. This munition type is in use with the NLD MoD.

The case study comprises the following parts:

- Threat: effects from incoming mortar,
- Donor: 155 mm M107, TNT-filled,
- Acceptor: 155 mm M107, TNT filled.

Three types of acceptors are identified, where each type is loaded by a specific mechanism, see Figure 6 for a visualization of these mechanisms:

I. Acceptor in neighbouring stack: the distance between donor and acceptor is relatively large, ranging from 10-100 cm.
II. Acceptor in same stack, one-on-one situation: the distance between donor and acceptor is minimal, maximum up to several cm's.
III. Acceptor in same stack, diagonal positioned: the distance between donor and acceptor is relatively small, but effects are enlarged because of jetting effects within the munition stack.

The reason why these mechanisms all have to be included in the evaluation is because it is known that the casing of the donor article will fail in a specific way. At first the casing will expand in an elastic-plastic manner. Only then fragmentation is initiated, but as munition articles in general are cylindrically shaped fragmentation starts with the formation of long, slender strips. Only at a later instance the casing fragments into smaller parts. So, only in mechanism I the acceptor munition is impacted by distinct fragments in combination with a possible blast wave. However, for mechanism II the acceptor is impacted by either a still intact, expanding donor casing or a casing in its initial stage of fragmentation. The influence of the distance between donor and acceptor on the loading mechanism is experimentally confirmed and illustrated by witness acceptor cylinders which have been placed at different distances from a detonating donor, see Figure 7 [12]. The cylinders placed at only 20 or 40 mm are more or less loaded in a homogeneous way by the expanding donor cylinder, while at a distance of 70 mm the acceptor cylinder is impacted by distanced fragments.

The loading of the acceptor at the diagonal (Mechanism III) is comparable to the loading in mechanism II, although in this situation the donor casing is forced into the open area in between the articles, but still impacting the acceptor in a homogeneous way, see Figure 6 (right).

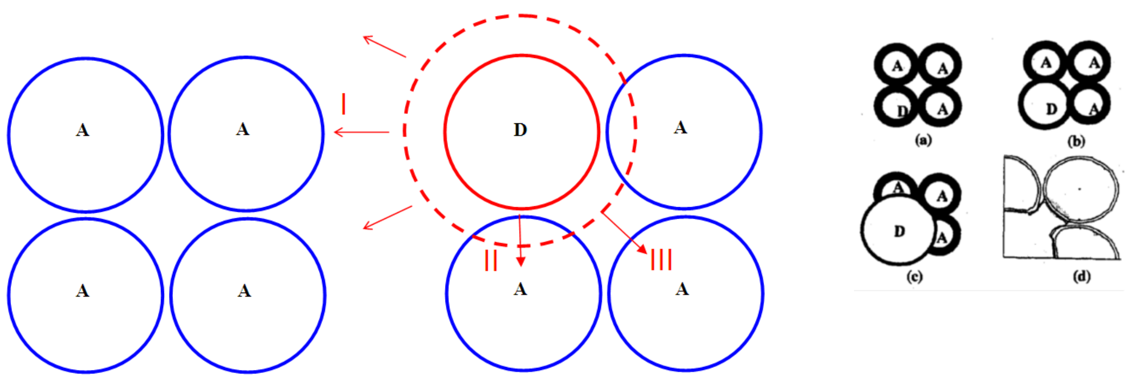

Figure 6 Schematic overview of the three mechanisms involved in a sympathetic reaction situation in a munition storage (left). Loading of diagonal (Mechanism III) illustrated by simulation (right) [4].

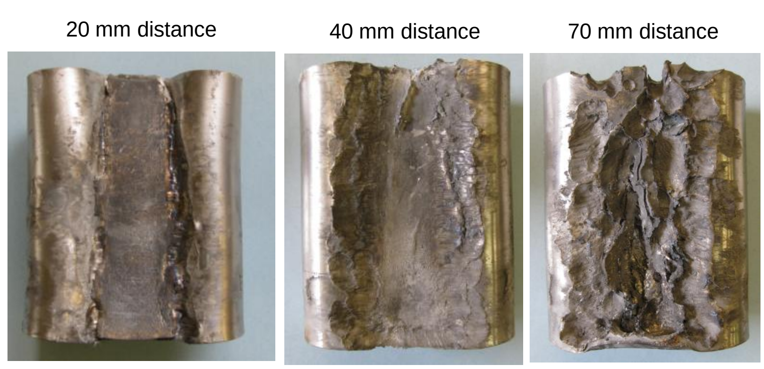

Figure 7 Steel cylinders showing the effects of the loading of a detonating donor at increased spacing [12].

Results case study

The results of the evaluation are covered in Table 2. A separate discussion of all distinct analyses would be too extensive for the present paper. However, some of the important results are extracted for discussion, although some only briefly.

Tabel 2 Condensed results of analysis.

Mechanism	Relevant threat	Result
I	Shock to Detonation Transition (SDT)	For impact by fragments from a detonating donor M107 the occurrence of SDT is highly likely for a range of fragments shapes and impact angles on the surface of an acceptor M107. This is valid for distances up to where the maximum fragment velocity is reached
	Acceptor casing penetration	For impact by fragments from a detonating donor M107 the casing of the acceptor casing will be penetrated for a large variety of fragment masses and shapes and under a large range of impact angles
	Blast	The reflected peak pressure loading the acceptor exceeds the critical shock pressure of the explosive fill of the acceptor, resulting in sympathetic detonation up to distances of about 2 meters (distance indicative only)
II	Sympathetic reaction, one-on-one (homogeneous loading of acceptor)	The loading of the acceptor by the expanding donor casing does not result in SDT. High-rate loading of the acceptor however could result in initiation, but is not (yet) included in the evaluation
III	Sympathetic reaction, diagonal (homogeneous loading of acceptor)	The loading of the acceptor by the expanding donor casing (being forced into the open space in between the articles in the stack) results in SDT

Discussion

Tabel 2 clearly shows that the difference in distance between donor and acceptor drives the loading of the possible initiation of the acceptor. At slightly larger distances between donor and acceptor, multiple initiation mechanisms are becoming relevant as the fragmentation of the donor casing develops, fragment velocity increases and a blast wave has the time to form. This, however, does not imply that in case of substantially smaller distances the loading of the acceptors by a detonating donor is less relevant. Evaluation of the case study for all three mechanisms shows that sympathetic detonation is typical for the M107 as used in the study. Since the M107 is classified as HD1.1 this is no surprise, but the current evaluation gives closer insight into the mechanisms that play a role in the development of a mass detonation. This information forms the basis for finding and engineering optimal mitigating materials or structural solutions.

At TNO, recent studies have focused on materials that could play a role in the prevention of sympathetic detonation for Mechanisms II and III, in which the acceptor is loading by the, still intact, but expanding casing. The homogeneous loading of the acceptor casing that was observed from experiments guided the search for the right materials. Mitigating materials and structures have previously been under study at TNO [2], but focused more on the effects that are relevant for Mechanism I, see also Figure 2.

Mitigating materials

Materials that are capable of reducing the energy from a moving object with a homogeneous front surface are found in the area of foams and rubbers. Therefore, in recent projects these types of materials have been under study. Small-scale experimental programs have been set-up to identify the behaviour of these types of materials, when placed in between a detonating donor cylinder and inert or live acceptor cylinders.

Initial results show the potential for application of foams. The rubber material was found to be transferring shock waves with only limited attenuation, therefore the focus has been on polyurethane (PUR) and aluminium foams primarily, see Figure 8.

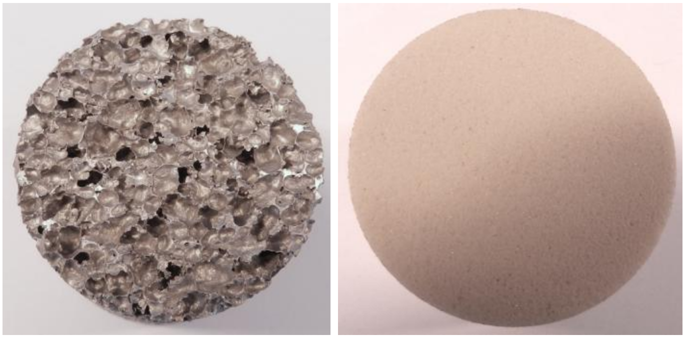

Figure 8 Close up photographs of aluminium (left) and PUR (right) foam.

In the experimental program the distance between donor and acceptor was varied. Steel cylinders with 5 mm thick walls were filled with approximately 500 grams of Semtex10. In case of live acceptors Semtex10 was also used as explosive fill. The inert acceptors were filled with sand. With 70 mm of either aluminium or PUR foam in between the detonating donor and acceptor, sympathetic detonation could be prevented. At 40 mm distance, a partial detonation occurred for the PUR foam, while for the aluminium foam a full detonation was found.
From the experiments with the inert acceptors the loading of the acceptor casings could be revealed and compared against earlier experiments without the mitigating materials. From Figure 9 below the difference is clear. Although the foams do not prevent loading (and thus deformation) of the acceptor casing, fragment impact, or direct impact from the still intact donor casing is prevented completely thus preventing SDT at these distances.

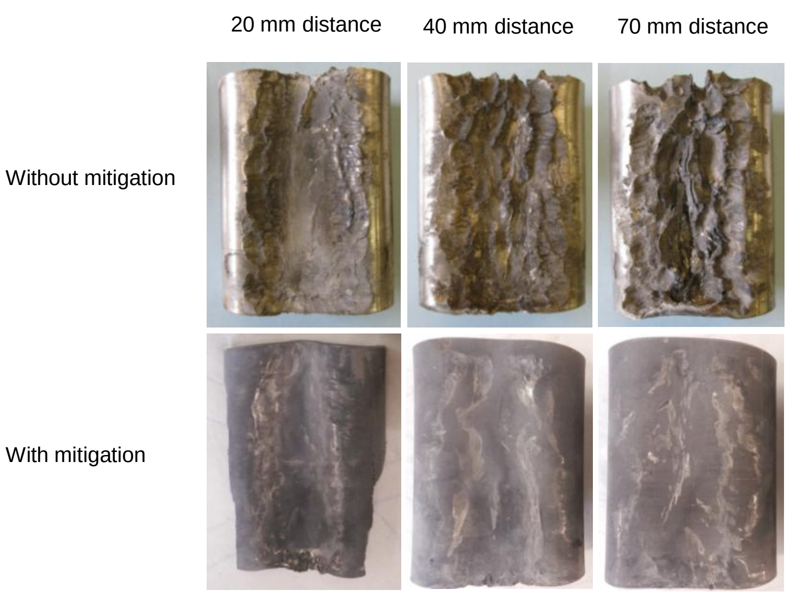

Figure 9 Difference in loading on steel witness cylinders at different distances with and without mitigating foams (results aluminium and PUR foam comparable).

To reveal the phenomena that occur in the foam during the detonation of the donor and the subsequent expansion of the donor casing, ANSYS-Autodyn (version 13.0 and 14.0) simulations have been performed on the exact configuration as during testing. The simulations revealed interesting features of the behaviour of the foams. In Figure 10 (left) it is shown that as the casing expands a compressive loading is developed

in the foam, acting against the direction of the expanding donor casing. This reduces the velocity of the expansion. Further, the volume of the foam that is compressed acts as a pressure wave travelling through the foam in advance of the expanding donor casing. This pressure wave reflects onto the acceptor casing (Figure 10, centre) and then moves towards the, still-expanding, donor casing. The reflected pressure wave impacts the expanding donor casing (Figure 10, right), upon which the velocity of this casing is substantially reduced, thus reducing the severity of the impact of the donor casing onto the acceptor casing. A plot of the velocity of the expanding case vs. time is shown in Figure 11. The numbers (1), (2) and (3) in this graph represent the moments in time corresponding to the three images in Figure 10.
The properties of the foam that play a role most likely are the compression stress – volume curve, the density of the foam and the sound velocity of the foams' base material. A parameter study on these properties still has to be performed but will enable optimization of the application of foam materials, resulting in a reduced energy and impulse transfer from the detonating donor to the acceptor.

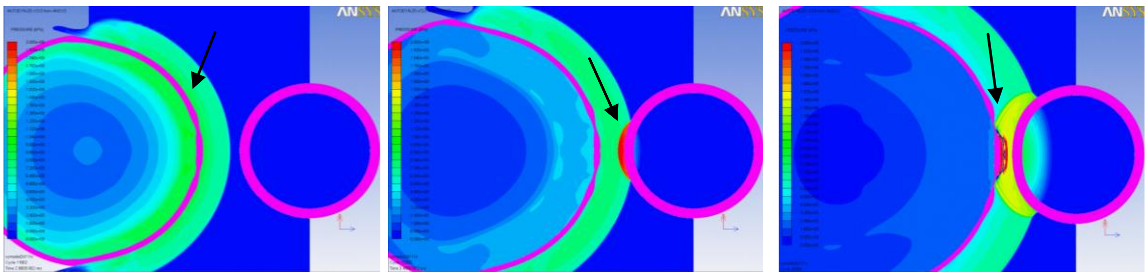

Figure 10 Autodyn simulations reveal the behaviour of the foams: Left: compressive loads in the foam act against the expanding donor casing; Centre: the pressure wave in the foam reflects from the acceptor casing moving towards the still expanding donor casing; Right: the reflected pressure wave impacts the expanding donor casing.

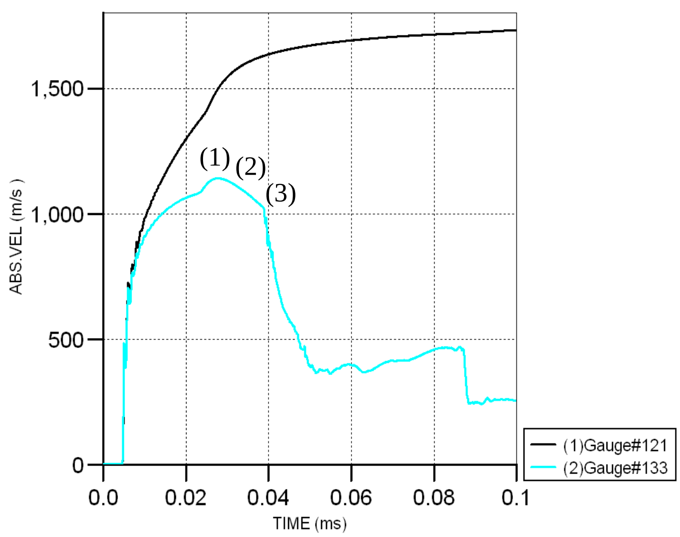

Figure 11 Typical velocity of the expanding donor casing as a function of time. Black line: no mitigation; Blue line: PUR mitigation.

Conclusions

It is important to put the research and development on Insensitive Munitions in the context of the military operations. Therefore, an investigation has been performed to quantify the operational consequences of a mass detonation of a munition storage to a maximum of 4000 kg in an out-of-area compound. This is done for a case study addressing a mortar attack on the munition storage in a virtual compound environment. The quantification is done in terms of injury and lethality of military personnel and to the infrastructure. The operational consequences can be substantially lowered by taken mitigating measures to reduce the mass detonation to only a limited event.

It is shown that, by the ability to deploy and store IM munitions and/or additional mitigation measures on a compound, the amount of fatalities and injured can substantially be reduced, enabling an efficient continuation of the mission.

A Sympathetic Reaction Toolbox is under development in which a range of engineering tools are covered. The tools focus on the mechanisms that occur in sympathetic reaction situations. Attention is given to how external threats initiate a reaction in a donor munition article. But also how the effects from a reacting donor load neighbouring munition by fragment impact, blast loading and by the expanding donor casing. The detailed technological work on these mechanisms and the phenomena that lead to a sympathetic detonation delivers the right information to find solutions to prevent sympathetic detonation by means of mitigating measures.

Several types of mitigating materials are investigated, based on the effects that occur at close range of a detonating donor. The elastic-plastic expansion of the donor casing loads the mitigating material in a more or less homogeneous way, depending on the distance between the article. High-performance foams have been experimentally tested and their behaviour has been numerically simulated, showing great potential for the application of these types of materials.

By putting all the work on Insensitive Munitions in the right perspective, the right stage is set and should motivate and challenge researches in their activities, which, in the end, are being performed to protect the war fighter in an intrinsic dangerous environment.

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