PHYSICAL EFFECTS AND CONSEQUENCES FROM DETONATIONS AND LESS VIOLENT MUNITION RESPONSES – AN OVERVIEW

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Abstract

An increasing number of warhead designs shows a less violent response than Detonation (type I) in cook off or impact scenarios. In order to quantify the safety benefits, MSIAC is working on improvements in the risk management of such munitions. For Deflagration (type IV) and Explosion (type III) reactions, only limited quantitative information exists about the physical effects and consequences. This includes primary fragmentation, internal pressure loads and projection of debris from storage structures, as well as external blast (or pressure) waves and thermal effects. In storage conditions, the larger scale and confinement introduces additional complexities. This paper discusses relevant data and presents a first step towards the development of models.

Due to the reduced reaction rate, fragmentation typically leads to larger strip-like fragments, but with a smaller velocity. Trajectory calculations have been carried out to illustrate the influence on impact distances. Tests have shown that impact distances can even increase due to a smaller deceleration by airdrag. The occurrence of a small number of fragments with a large impact distance raises questions about appropriate definitions for safety distances. Compared to detonations, break-up of storage structures will occur at higher loading density (NEQ per volume) for less violent munition responses. Detailed knowledge about the storage construction and in particular vent areas, is essential to determine the overall response. As for primary fragments, structural debris will increase in size and reduce in velocity, however the debris throw may also become more directional. A number of adaptions to the Debris Launch Velocity (DLV) equation are discussed to account for sub-detonative behavior. These are a reduction in either the available energy for acceleration or a reduction of the effective acceleration path length. External blast will reduce in strength, which can be represented with reduced TNT equivalencies, but more appropriate are models that account for a lower reaction rate and lower explosion overpressures. The potential of the Multi-Energy method (originally developed for gas-explosions) has been investigated.

We recommend that standardized IM tests are extended with a more detailed measurement of fragmentation and blast for the purpose of model validation. The IM test standards could also specify more quantitative measures to help define the munition response in terms of reaction rate. It is also recommended that the international community focus on full scale testing of IM. CFD and engineering models could focus more on internal pressure development and structural response for limited reactions rate. We hope that the findings in this paper will aid the development of Quantity Distances (QD) and risk management of future munitions for a range of responses.

Introduction

An increasing number of warhead designs shows a less violent response than detonation in cook off or impact scenarios. In order to quantify the safety benefits, MSIAC is working on improvements in the risk management of such munitions.

The Insensitive Munitions European Manufacturers Group (IMEMG) has produced an overview of national and international Insensitive Munitions (IM) requirements (Figure 1). This overview shows that for most standardized threats as given in [AOP-39, 2010] the criterion is to have a response equal to or less than a Burn (type V), Deflagration (IV), or Explosion (III).

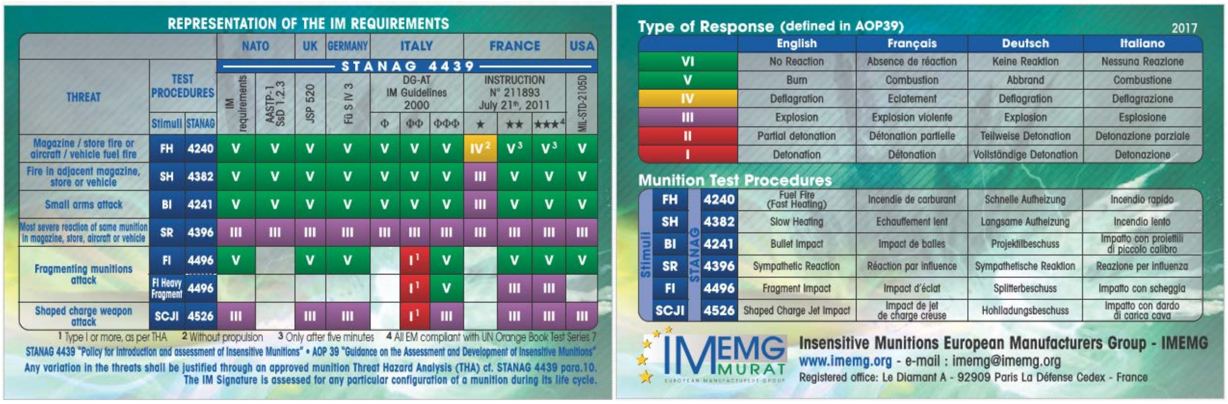

Figure 1. Overview of national and international IM requirements (IMEMG, 2017)

For these reaction types only limited quantitative information exists about the physical effects and consequences. This includes primary fragmentation, internal pressure loads and projection of debris from storage structures, as well as external blast (or pressure) waves and thermal effects. In storage conditions, the larger scale and confinement introduces additional complexity. This paper discusses relevant data and presents a first step towards the development of models.

Primary fragmentation

Detonation

The detonation of a warhead typically leads to well reproducible fragmentation effects. Established models are available to estimate the fragment launch velocity, mass and angular distribution, such as those from Gurney, Mott, and Taylor [Carlucci, 2008 & TP16, 2012]. This information is the basis for weapon effects calculations, but also for explosive safety risk analysis [AASTP-4, 2016]. A sympathetic detonation of a stack of munitions will show a significantly different fragmentation pattern than a single shell. [TP16, 2012] gives rough guidance how the fragment characteristics change, both fragment masses and velocities will typically increase.

The launch velocity depends on the explosive reaction rate, warhead burst volume and the fragment explosive contact surface area. While the explosive is reacting, the volume expansion of the explosive products gases pushes the case wall and makes it accelerate. The velocity that it achieves depends on the force history that the case wall receives before the case wall bursts. If the explosive fully detonates, it quickly accelerates the case wall in a reproducible manner. The final fragmentation size is quite small. The number of fragments increases with increasing wall velocity before burst. For a detonating munition, the case wall normally starts to fragment when the case wall has expanded to about two times the original explosive volume [Gold, 2007]. The fragmentation process continues until the case wall has expanded to about three times the original explosive volume. The fragmentation reaches it's final velocity sometime during the fragmentation process. This is because the expanding gases are rarefied due to release of pressure when the case wall fractures.

Less violent munition response

Deflagrations and explosions may still rupture the munition casing, but fragmentation is typically limited to just a few large items with a relatively low velocity. The fragments typically have a plate- or strip-like shape, with a thickness equal to the original warhead casing thickness, thinned by expansion up to the burst volume. The thickness of the wall casing indicates the approximate expansion of the case at the time of burst [Baker, et al., 2009]. The largest fragments may also originate from closure parts of the warhead (base plate or nose) and not from the cylindrical part of the casing.

For subdetonative explosive response, the fragments normally do not reach the same velocities as detonating munitions [Baker, et al., 2009]. This because the explosive reacts more slowly and the case wall breaks before complete reaction of the explosive is complete. As the case wall is moving much slower than a full detonative event, a fewer number of cracks and larger fragments result. The thickness of these fragments is somewhat thinner than the original case wall due to thinning during the case expansion. For deflagrating munitions, this usually results in a very few number of large fragments that typically have a plate- or strip-like shape. Some success has been achieved at predicting their shapes and sizes using fully three dimensional high rate continuum modeling [Baker, et al. 2009].

The general expectation is that for less violent munitions responses, the effects and consequences will reduce. [Baker, et al., 2009] have shown that this is not necessarily the case for fragmentation. They describe tests with M107 155 mm Comp B filled artillery shells with a non-standard initiation by a shaped charge. The larger fragments created in the sub-detonative response travelled further due to a lower deceleration by air drag. An example of a 840 g steel fragment reaching 1824 m is given (Figure 2), thereby greatly exceeding the established Hazardous Fragment Distance (HFD) and the Maximum Fragment Distance (MFD)[1] relevant for a detonation of this munition. It was shown that the fragment must have travelled in a spin-stabilised edge-on orientation.

This observation raises the question what is an appropriate methodology to determine safety distances. On the one hand for this response the MFD is very large, on the other hand, due to the small number of (large) fragments, the hit probability and consequently the HFD is relatively small.

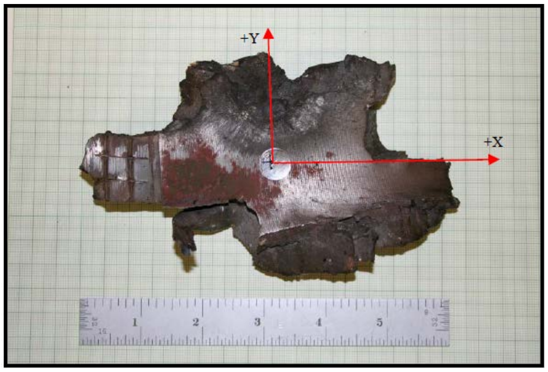

Figure 2. Fragment found at 1824 m after sub-detonative response of artillery shell [Baker, 2009]

[Kinsey, 1992] and [Chick, 1992] provide some experimental characterization of deflagrating munitions during the deflagration process. They quantify the large strip-like fragments that are produced. The fragment velocities are shown to be much slower, having velocities of between 1/3 to 1/10 of the same detonated munition.

Another example is a test series with black powder filled ordnance by [Crull, 2004]. She applied the aforementioned fragmentation models (Mott and Gurney) with an appropriate TNT equivalence for black powder. This resulted in an over-prediction of both the number of fragments and the initial velocity. The fragment sizes and the throw distances were however underpredicted.

Also noteworthy is the development of “dial-a-yield technology” [Arnold, et al., 2011]. This technology enables the selection of a desired munitions response between deflagration and detonation. A proof of concept was developed and experiments showed that blast and fragmentation effects could be tuned between low and high output.

[1] HFD = 137 m, MFD = 801 m

The main aim of the standardized IM tests [AOP-39, 2010] is to assess whether a munition passes certain fragment criteria, not to characterize the (remaining) fragmentation hazard in any level of detail. We recommend however to extend IM tests with measurement of the fragment mass, velocity, and angular distribution, for the purpose of model validation. This can be done by introducing more witness plates, high speed video and detailed fragment collection in unobstructed parts of the test arena.

Trajectory analysis
In order to get an idea what a sub-detonative response means for various types of warheads we have conducted a range of trajectory calculations. The results have been reported in an MSIAC limited report [Van der Voort, 2018].

Internal pressure loads and secondary debris

Detonation: introduction
Experimental and theoretical research into the effects of accidental detonations in ammunition storage magazines is coordinated and conducted in the Klotz Group (KG), an international cooperation of explosives safety experts. The work has led to various numerical approaches [Weerheijm, et al., 2017] and the Klotz Group Engineering Tool (KG-ET) [Van der Voort, et al., 2013]. The KG-ET predicts the debris throw hazard based on empirical relations for debris mass-, velocity-, and angular distributions.

The relevant phenomena are:

- The magazine walls will first be loaded by a shockwave followed by multiple reflections. This is typically the main reason for structural break-up and formation of debris.
- After a short rise time, walls will be loaded by the Quasi Static Pressure (QSP) as a result of the expanding detonation products. This is typically the main reason for the acceleration and the resulting debris launch velocity.
- Afterburning plays an important role for explosives with a negative oxygen balance. For low loading densities (charge mass divided by internal volume) there is enough oxygen in the magazine for the combustion of any remaining unreacted substances. In this case the released energy will be close to the heat of combustion. For high loading densities, there is not enough oxygen for a significant after burning, and the released energy will be close to the (smaller) heat of detonation. This is illustrated in Figure 4.
- Doors or specifically designed vent panels will fail and reduce the internal pressure. The vent openings increase as the panels move away from their initial positions.

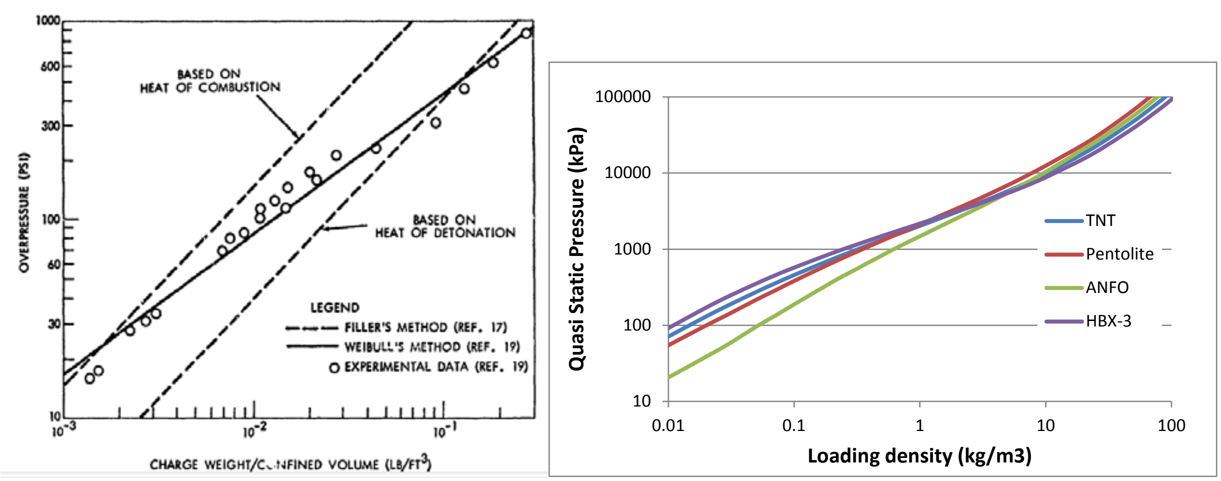

Figure 4. Overpressure reached in closed chamber after TNT detonation. Left: original data from [Procter, 1972]. Right: results for other explosives [AASTP-4, 2016].

When the storage magazine is a reinforced concrete structure we can distinguish between the following four regimes [Weerheijm, et al., 2002]:

- Up to a loading density in the order of 0.1 kg/m^3 most structures are able to contain the explosion. The extent of this regime is very much dependent on reinforcement properties and the presence of vent openings
- The gas pressure overloading regime reaches up to a loading density of about 1 kg/m^3. In this regime the structural response is important. The debris velocity is typically below 100 m/s.
- The blast impulsive overloading regime reaches up to 16 kg/m^3, where launch velocities up to about 300 m/s may occur.
- In the shock overloading regime, beyond 16 kg/m^3, the break-up is determined by local effects. Launch velocities may reach well into the supersonic regime. A significant part of the structure breaks up in aggregate size debris or dust.

In order to prepare for a discussion about less violent munition responses we will revisit data and models for detonations. The focus will be on internal pressure loads and debris launch velocity.

Detonation: test data

Recenty [Oswald, 2017] gave an overview of all available gas pressure test data. This included 18 test series with over 130 tests. Loading densities varied between 0.016 and 6.4 kg/m^3, while covered and uncovered vent areas were used with $0.01 < A_v/V^{2/3} < 1$ (A_v = vent area, V = internal volume). Several explosives were used, but the majority was TNT and C-4. Oswald also compared the data to various modeling approaches:

- ConBlast, which is an improved version of SHOCK and FRANG
- Blast-X
- UFC 3-340-02

The main differences between the test data and models was subscribed to early venting of the QSP which is not accounted for in the models. Furthermore there are various CFD codes that have been applied to calculate pressure loads in confined and vented explosions, examples are APOLLO and ANSYS Autodyn.

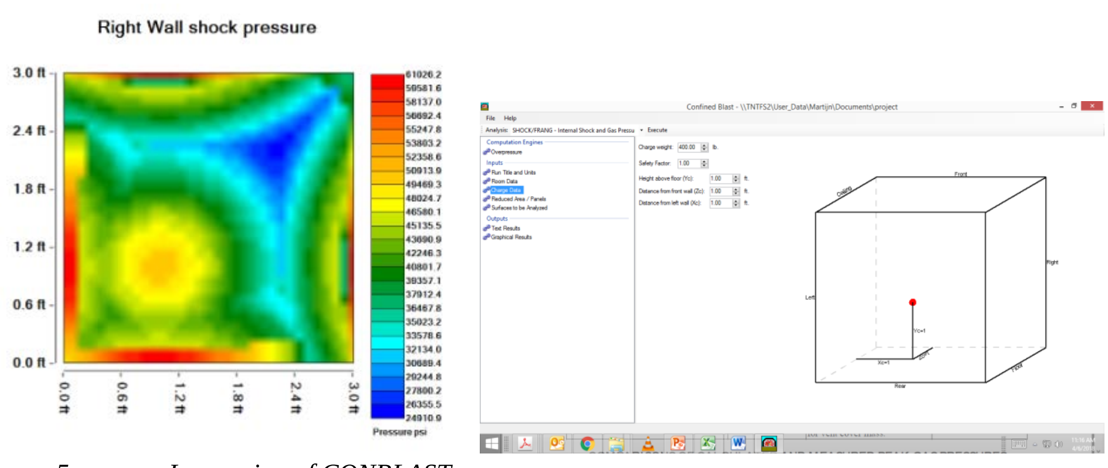

Figure 5. Impression of CONBLAST.

In another type of test a high explosive charge is initiated centrally in a cubical box, and the launch velocity of a steel slab placed on the top is measured. These Debris Launch Velocity (DLV) tests have been conducted for various loading densities (between 0.016 and 16 kg/m^3), and areal mass of the slab (between 120 and 480 kg/m^2). Pentolite and PETN were the main explosives used.The results showed that the gas pressure developed in the chamber is the main reason for the slab acceleration, while the shock impulse is only of secondary importance. Analysis of the test results led to the DLV formula [Dörr, 2002]:

$$\mathrm{DLV} = 525 \cdot \sqrt{\frac{\gamma \cdot L_c}{m}} \qquad \text{(m/s)} \qquad (1)$$

With:

Loading density	$\gamma = Q/V$	(kg/m^3)
Charge mass	Q	(kg)
Internal volume	V	(m^3)
Slab areal mass	$m = M/A$	(kg/m^2)
Slab mass	M	(kg)
Slab area	A	(m^2)
Characteristic length	$L_c = V^{1/3}$	(m)

Figure 6. Impression of slab launch tests [Dörr, 2002].

A number of variations to the initial test set up were carried out. Changing the position of the explosive charge in the chamber only led to small either positive or negative deviations in launch velocity. This observation once more confirmed that the gas pressure is more important than the shock impulse, at least for the loading densities tested.

Clamped tests were carried out with concrete slabs mounted to the detonation chamber to simulate the attachment of building walls at the connecting corners. This resulted in a significant increase in launch velocity of about 30%. It was hypothesized that this could either be caused by delayed venting or a prolonged gas pressure loading phase. The first option was tested by performing tests with a free slab but with a frame placed around it in order to prevent direct venting. It appeared that the 30% velocity increase could be fully explained by delayed venting.

A next variation was made by testing rectangular detonation chambers instead of cubicle ones. [Van Doormaal , 2003] performed numerical simulations that supported a correction factor to the DLV formula to make it applicable to rectangular detonation chambers:

$$\mathrm{DLV} = 525 \cdot \sqrt{\frac{\gamma \cdot L_c}{m}} \cdot \sqrt{\frac{\Pi_{cube}}{\Pi_{rect}}} \qquad \text{(m/s)} \qquad (2)$$

Perimeter of a slab for a cubicle (reference) detonation chamber	Π_{cube}	(m)
Perimeter of a slab for a rectangular detonation chamber	Π_{rect}	(m)

The background for this correction is that the area through which detonation products vent during slab acceleration is directly related to the slab perimeter.

In a next phase five slabs (four on the sides and one on the top) were launched from a cubical arrangement, instead of just the top slab. Loading densities varied between 1 and 8 kg/m^3. These multiple slab launch tests showed that due to the increased venting the launch velocity was about 15 % lower than given by Eq.1. As part of the multiple slab launch tests, mixed mass arrangements where used. It appeared that if one of the slabs was twice lighter than the other slabs (15 versus 30 mm steel plates), this slab would obtain a launch velocity almost identical to a single slab launch, i.e. Eq. 1. The velocity of the heavier slabs was clearly smaller.

[Forsén, 2004] performed tests, with two of the aforementioned variations conducted at the same time. In this test series multiple slabs were launched not only from cubical but also from rectangular arrangements..

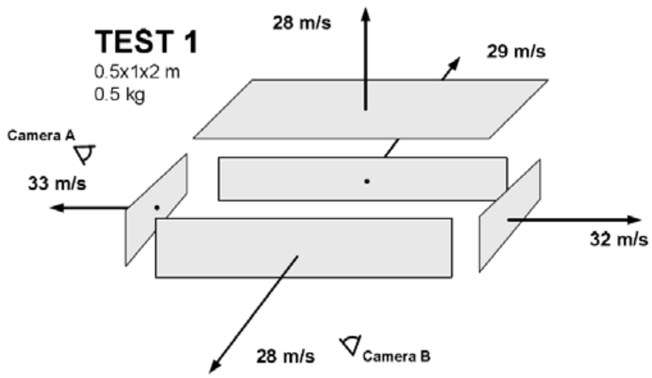

Figure 7. Multiple slab launch test with rectangular arrangement [Forsén, 2004]

In Figure 8 the launch velocities measured by [Forsén, 2004] are shown together with launch velocities from a cubical arrangement by [Dörr, 2003]. The rectangular arrangement had dimensions of 2*1*0.5 m. The launch velocities observed for the cubical arrangement (red data points) are clearly smaller than the DLV formula (Eq.1, black curve), but correspond reasonably well when the multiple slab launch correction (-15%) is applied. For the walls of the rectangular arrangement, an additional correction was applied ($\sqrt{\frac{\Pi_{\text{cube}}}{\Pi_{\text{rect}}}}$). For the long walls (green curve and green data points) this means a reduction, while for the short walls (orange curve and orange data points) this means an increase. By coincidence, the increase for the short walls brings the velocity back to about the same value as given by Eq.1 (black curve).

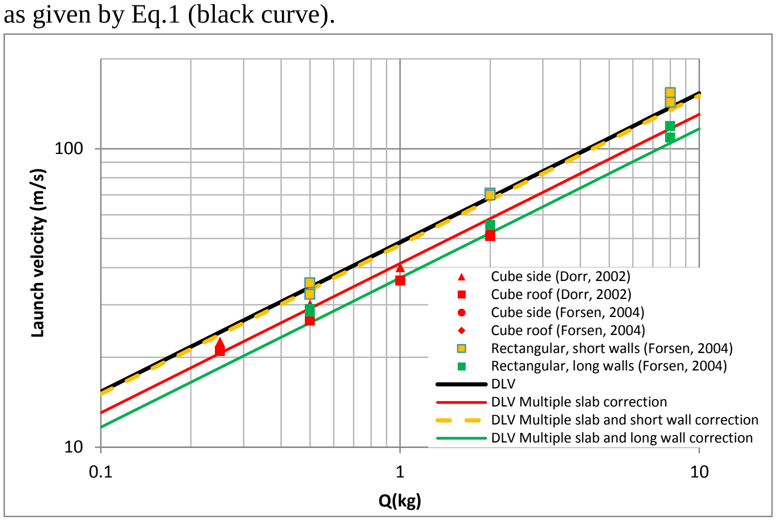

Figure 8. Slab launch velocities from multiple slab launch tests with cubical and rectangular arrangements together with model predictions and correction factors discussed in the text.

These results show that the correction factors for multiple slab launch and rectangular arrangements can reasonably well be applied simultaneously.

Detonation: derivation of energy based DLV equation

Although many references claim that the DLV equation (Eq. 1) is based on the assumption that a fixed fraction of the available energy is transferred to kinetic energy, a thorough derivation is missing. The MSIAC limited report [Van der Voort, 2018] presents two derivations, one based on available energy, one based on overpressure.

Less violent munition reponses

The smaller reaction rate for less violent munition responses will lead to weaker shock- or pressure waves. Also a larger rise time of the QSP can be expected. The reaction phase may also coincide with the venting phase, so that the maximum pressure reached in the magazine becomes dependent on the balance between combustion and venting. A good illustration of this last regime is a test series which involved the ignition of M1 propellant in reinforced concrete magazines with a vent area [Farmer, et al., 2015]. Dependent on the loading density and size of the vent area, it was found that combustion could lead to over-pressurization and break-up of the magazine including significant debris throw, as shown in Figure 12.

Figure 12. Initial setup (top) and results (bottom) from test with 540 kg M1 propellant (each barrel initiated) [Farmer, et al., 2015].

Compared to detonations, break-up of storage structures will occur at higher loading density (NEQ per volume) for less violent munition responses.Detailed knowledge about the storage construction and in particular about the properties of vent areas, is essential to determine the overall response. As for primary fragments, structural debris will increase in size and reduce in velocity, however the debris throw may also become more directional.

The derivations presented by [Van der Voort, 2018] may be a good starting point to develop engineering models for the debris launch velocity for the various munition responses. A possible outcome could be that the available energy or the acceleration path length would be reduced in comparison to detonations. Figure 13 illustrates this approach and also shows that, besides structural information, quantitative values for reactions rates are needed as input.

Although some qualitative information can be found in [AOP-39, 2010], quantitative data is needed to develop models and perform calculations.

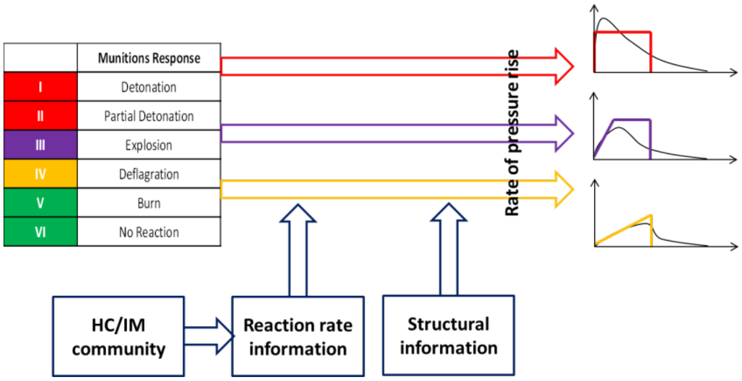

Figure 13. Ilustration of munition responses and related internal pressure loads as a basis for future models for debris launch velocity.

External blast

Detonation

The last topic is external blast. For detonations well established engineering models are available to estimate blast parameters such as the peak overpressure and positive phase impulse as a function of the scaled distance Z:

$$Z = \frac{R}{Q^{1/3}} \qquad (9)$$

With R the distance (m) and Q the mass of a TNT charge (kg). A well-known example is the US Blast Effects Computer (BEC) [TP17, 2005] & [AASTP-4, 2016].

The usual reference case is a hemispherical surface burst; the detonation of a TNT model charge on a surface. The concept of TNT equivalency is commonly used to represent situations that deviate from this reference case. [Peugeot, 2006], [Simoens, 2011], and [Collet, 2018] have described various important factors that play a role, as well as test methods for TNT equivalency and their limitation. Table 2 gives a summary of the factors that influence TNT equivalency.

Table 2. Factors that influence TNT equivalency.

Property		**Reference case**	**Other examples / description**
Energetic Material level	Energetic Material	TNT	RDX, C-4, black powder
	Additives	None	Aluminium particles
Boundary conditions	Charge shape	Hemispherical	Cubical, Rectangular, Line charge
	Geometry	Surface burst	Free air burst, complex geometry
	Surrounding medium	Air	Water
Initiation and response	Initiation location	Central	Side
	Initiation type	Initiator	Cook-off, Impact
	Energetic Material response	Detonation (I)	Partial detonation (II) Explosion (III), Deflagration (IV), Burn (V)

Munition level	Casing material	NA	Steel, Tungsten, Aluminium, DU
	Casing thickness	NA	Self-Explanatory
	Distributed charges	NA	Main charge, booster, rocket motor
Stack level	Stacking configuration	NA	Orientation (horizontal or vertical) and spacing
	Packaging	NA	Wood, cardboard
Storage level	Barriers	NA	Concrete
	Magazine construction	NA	Wall thickness, volume, reinforcement, venting
	Earth cover	NA	Earth cover thickness
	Barricade	NA	Barricade distance and height

Besides the factors in Table 2, the TNT equivalency also depends on the physical effects of interest, e.g. the blast peak overpressure or impulse, or the ability to crush a material. The way the factors in Table 2 affect blast wave propagation may also depend on the distance from the explosion. For example the shape of the explosive is highly influential close in to the explosion, whereas the effects diminish in the far field [Simoens, 2011]. Similarly, the presence of additives like aluminium particles such as in PBXN-109 will result in afterburning which leads to a slower decay of the blast wave compared to TNT blast [Collet, 2018].

Table 2 shows that for ammunition storage scenarios many factors have an influence on the yield. As an illustration we will show results from the 40 tonnes trial [Swisdak, 2003]. In this trial 462 Mk 82 bombs were detonated inside a brick walled, concrete roof magazine. The total Net Explosive Quantity (NEQ) of the event was 40,467 kg of Tritonal. Figure 14 shows a comparison of the blast measurements with predicted blast from a hemispherical charge of 40,467 kg TNT. The yield clearly depends on the distance, it is small close-in, but approaches 1 in the far field (0.6 to 0.9). Although Tritonal has a TNT equivalency (for overpressure) of 1.07, the combined effect of casing and magazine reduce the yield substantially below 1. Swisdak has shown in his paper that the yield has been lower than 1 for all tested above ground structures. Using the NEQ as the basis QDs therefore seems to be a simple and conservative approach.

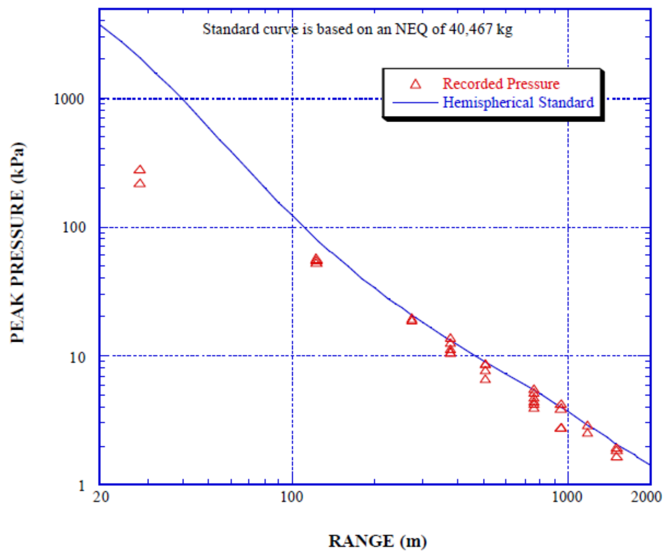

Figure 14. Peak overpressure versus range. Measurements for test with 40,467 kg Tritonal. Hemispherical blast model for 40,467 kg of TNT [Swisdak, 2003].

Standards for safe storage of ammunition, such as [AASTP-1, 2015] and [AASTP-3, 2009], allow to use TNT equivalency to account for these factors. However, in practice most nations simply use the mass of all energetic material in a munition as input for Quantity Distance calculations. Only in some cases adaptions are made; an example is the exclusion of a rocket motor when testing shows that it does not contribute to the detonation of the main charge. It should also be mentioned that some of the factors in Table 2 are accounted for in other ways, e.g. [TP17, 2005] has blast relations that account for the reducing effect of various types of magazines, including Earth Covered Magazines (ECM).

Less violent munition reponses

Another large deviation from the reference case occurs if the reaction is not a detonation. For less violent munition responses the concept of TNT equivalency may still work, but it could be more appropriate not to take a detonation as the starting point and to account for the lower reaction rates and explosion overpressures. A model that takes this into account is the Multi-Energy (ME) method [Van den berg, PGS2, 2006], which was originally developed for gas-explosions. This model presents blast curves for side-on peak overpressure, positive phase duration and dynamic overpressure. The curves are based on numerical simulation of a flame propagating at various speeds through a stoichiometric hydrocarbon-air mixture. The model distinguishes between 10 different explosion overpressures. Figure 15 presents the most important charts.

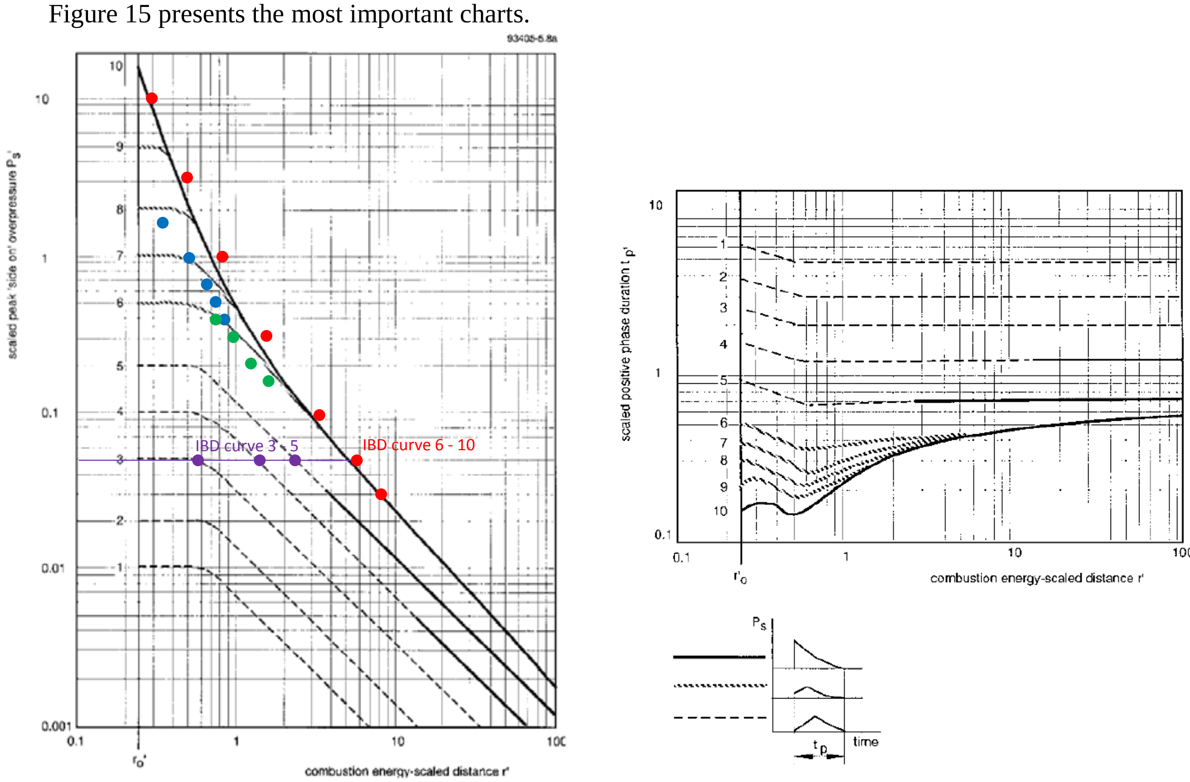

Figure 15. Multi-Energy blast charts [Van den berg, 2006]. Comparison with TNT blast (red). Comparison with MTV composition (WIC220): 1.5 kg (green) and 12 kg (blue). Inhabited Building Distance (IBD) prediction for curve 3 to 5.

The horizontal axis of the charts is the distance scaled by the ratio of combustion energy H (J) and ambient pressure P_0 (Pa):

$$Z_{ME} = \frac{R}{(H/P_0)^{1/3}} \qquad (10)$$

$$P_s' = \frac{P_s}{P_0} \quad (11)$$

The topmost curve (10) represents a gaseous detonation, while the lowest curve (1) represents a weak deflagration. The shading of the curves gives the shape of the blast waves; a solid line indicates a sharp shockwave, a dotted line represents more rounded pressure-waves. It can be observed that in the far field most pressure waves steepen and turn into shockwaves.
The top curves (6 to 10) coincide in the far field because the additional overpressure for the higher curves is dissipated in the near field. This aspect shows that an overpressure observed in the far field is not necessarily a reliable measure for near field blast. It also shows the limitations of using predictions based on TNT blast and equivalence.

In order to compare with TNT detonations we reformulate Z_{ME} in terms of Z:

$$Z_{ME} = \frac{\mathrm{R}}{(Q \cdot H/P_0)^{1/3}} = \frac{\mathrm{Z}}{(H/P_0)^{1/3}} \quad (12)$$

Table 3 presents values for Z and Z_{ME} for a number of explosion overpressures. The values for Z_{ME} have been calculated with the heat of detonation for TNT (H = 5.89 MJ/kg) and P_0 = 0.1 MPa. The first and second column have been plotted in Figure 14 and show a reasonable correspondence with the ME curve 10 for gaseous detonation.

Table 3. Range of overpressures with corresponding scaled distances for TNT and gaseous detonations.

P_s/P_0	Z (m/kg$^{1/3}$)	Z_{ME} (-)	Remark
0.03	33.8	8.69	
0.05	22.2	5.71	IBD for curve 6 – 10
0.1	13.5	3.47	
0.3	6.2	1.59	
1	3.2	0.82	
3	1.9	0.49	
10	1.15	0.30	

Another comparison has been made with blast measurements of Magnesium – Teflon – Viton (MTV) powder that is used in flares [Davies, et al., 2011]. The paper claims that their blast measurements suggest TNT equivalencies between 5 and 40%. Results for 1.5 and 12 kg of MTV (WIC220) have been shown in Figure 14. The green, respectively blue datapoints are not parallel to the detonation curve. This suggests a sub-detonative behavior which can probably be better described by selecting a lower ME curve than by applying a TNT equivalency (e.g. curve 7 or 8).

Another interesting comparison can be made with respect to the Inhabited Building Distance (IBD), as defined in [AASTP-1, 2015] as the distance at which an overpressure of 5 kPa is reached. This distance is equal for curves 6 to 10, but would significantly reduce for curves 3 to 5, and would even be zero for curve 1 and 2.

A more intensive comparison would also include the blast impulse and phase duration. Within the current study this has not been conducted. Further comparisons could also lead to advice which of the ME curves to use for a certain munition response.

Thermal effects

The current approach taken for HD1.6 and SsD1.2.3 is that QDs are based on the explosion of a single round or package and a burn of the rest of the stack. The thermal effects are currently represented by QDs that were originally developed for HD1.3 and are based on tests conducted using large quantities of propellant (Figure 16). We expect that these QDs lead to an overestimation when applied to SsD1.2.3 and HD1.6. It could therefore be considered to perform large scale fire validation tests with stacks of SsD1.2.3 and HD1.6.

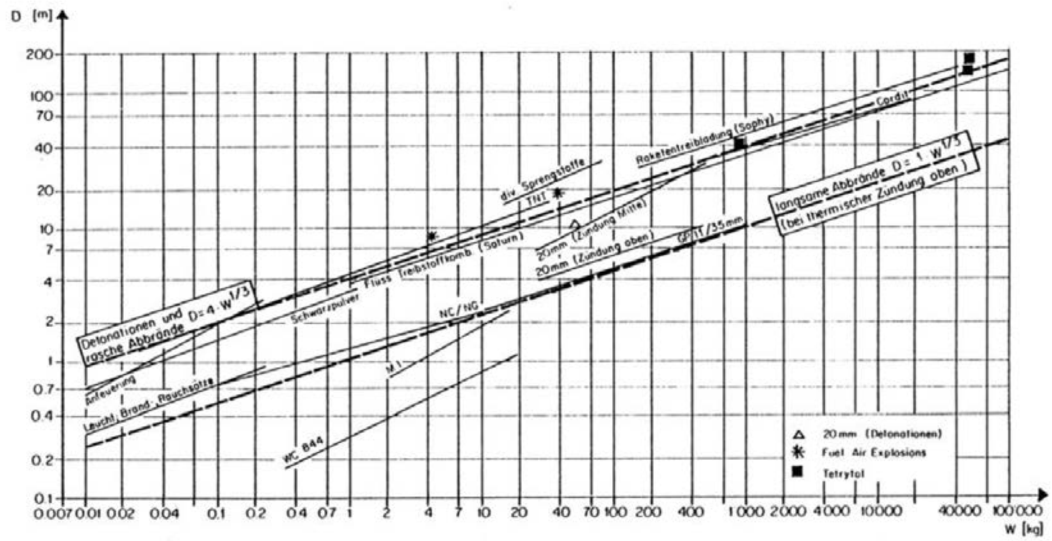

Figure 16. *Fire ball diameters for various propellants and explosives [AASTP-4, 2016]*

Conclusions and recommendations

Due to the reduced reaction rate, fragmentation typically leads to larger strip-like fragments, but with a smaller velocity. Trajectory calculations have been carried out to illustrate the influence on impact distances. Tests have shown that impact distances can even increase due to a smaller deceleration by airdrag. The occurrence of a small number of fragments with a large impact distance raises questions about appropriate definitions for safety distances. Compared to detonations, break-up of storage structures will occur at higher loading density (NEQ per volume) for less violent munition responses. Detailed knowledge about the storage construction and in particular vent areas, is essential to determine the overall response. As for primary fragments, structural debris will increase in size and reduce in velocity, however the debris throw may also become more directional. A number of adaptions to the Debris Launch Velocity (DLV) equation are discussed to account for sub-detonative behavior. These are a reduction in either the available energy for acceleration or a reduction of the effective acceleration path length. External blast will reduce in strength, which can be represented with reduced TNT equivalencies, but more appropriate are models that account for a lower reaction rate and lower explosion overpressures. The potential of the Multi-Energy method (originally developed for gas-explosions) has been investigated.

We recommend that standardized IM tests are extended with a more detailed measurement of fragmentation and blast for the purpose of model validation. The IM test standards could also specify more quantitative measures to help define the munition response in terms of reaction rate. It is also recommended that the international community focus on full scale testing of IM. CFD and engineering models could focus more on internal pressure development and structural response for limited reactions rate. We hope that the findings in this paper will aid the development of Quantity Distances (QD) and risk management of future munitions for a range of responses.

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