EXPERIMENTAL AND THEORETICAL BASIS OF CURRENT NATO STANDARDS FOR SAFE STORAGE OF AMMUNITION AND EXPLOSIVES

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ABSTRACT

NATO standards for the safe storage of ammunition and explosives contain tables with so-called Quantity Distances (QDs). These distances are aimed to provide an acceptable protection level to surrounding Exposed Sites (ES) in the event of an accidental explosion of a Potential Explosion Site (PES). The development of the standards took place over many decades by explosives safety experts. The QDs are based on the analysis of a large number of explosives tests- and accident data. Based on additional testing and analysis accomplished in recent years, a comprehensive and transparent overview of the basis for the QDs is necessary in order to validate them and to eliminate inconsistencies.

The Munitions Safety Information Analysis Center (MSIAC) conducted a study on the experimental and theoretical basis of QDs. This paper presents a structured approach to QDs, starting with the amount of munitions involved in the munitions response, and then treating each explosion effect separately.

Relevant references that support the standards have been analyzed. QDs have been compared to state-of-the-art prediction models for blast wave propagation and observed damage. The basis of those QDs that are dominated by fragments and structural debris is discussed as well. Planned changes to the NATO standards, such as the implementation of QDs for small quantities of explosives, are taken into account. Knowledge gaps have been identified and recommendations for long term development have also been made. A more detailed report as well as a repository of all references will be completed towards the end of 2016.

INTRODUCTION

The NATO CNAD Ammunition Safety Group, Allied Committee 326 (AC/326), Sub Group C (SGC) on “In-service and operational safety management” is responsible for developing NATO explosives safety criteria. Standards for safe storage of Ammunition and Explosives (AE) contain tables with so-called Quantity Distances (QD). QDs are aimed to provide an acceptable protection level to surrounding Exposed Sites (ES) in the event of an accidental explosion of a Potential Explosion Site (PES). Figure 1 gives a graphical overview of the most important terminology.

AC/326 SGC has adopted the UN transport Hazard Divisions (HD1.1 through HD1.6) as the basis for storage. Allied Ammunition Storage and Transport Publication 1 [AASTP-1, 2015] provides QDs for static storage as a function of the Net Explosive Quantity (denoted as NEQ or Q). HD1.1 comprises substances and articles which have a mass explosion hazard. HD1.2 substances and articles have a projection hazard but not a mass explosion hazard. The major hazard for HD1.3 is that of a mass fire. For HD1.4, which offers primarily a moderate fire hazard, separation distances are limited to fire fighting requirements. HD1.5 substances, which are very insensitive but do have a mass explosion hazard, are treated as HD1.1. For HD1.6 articles, which are extremely insensitive and do not have a mass explosion hazard, QDs are based on the more hazardous effects of either the detonation of a single article or a burn of the total NEQ. More detail on classification procedures can be found in the [UN Orange Book, 2015], the associated UN Manual of Tests and Criteria and [AASTP-3, 2009]. AASTP-1 also distinguishes Storage Subdivisions (SsD) in addition to the UN transport HDs.

The mixing rules in AASTP-1 prescribe how different HDs are aggregated when stored together. AE are also characterized with a compatibility group (CG) which is used to identify any storage restrictions.

Some AE are further characterized with a Sensitivity Group (SG) which applies to their propensity for prompt propagation from a nearby explosion, and leads in some cases to restrictions in the application of QDs.

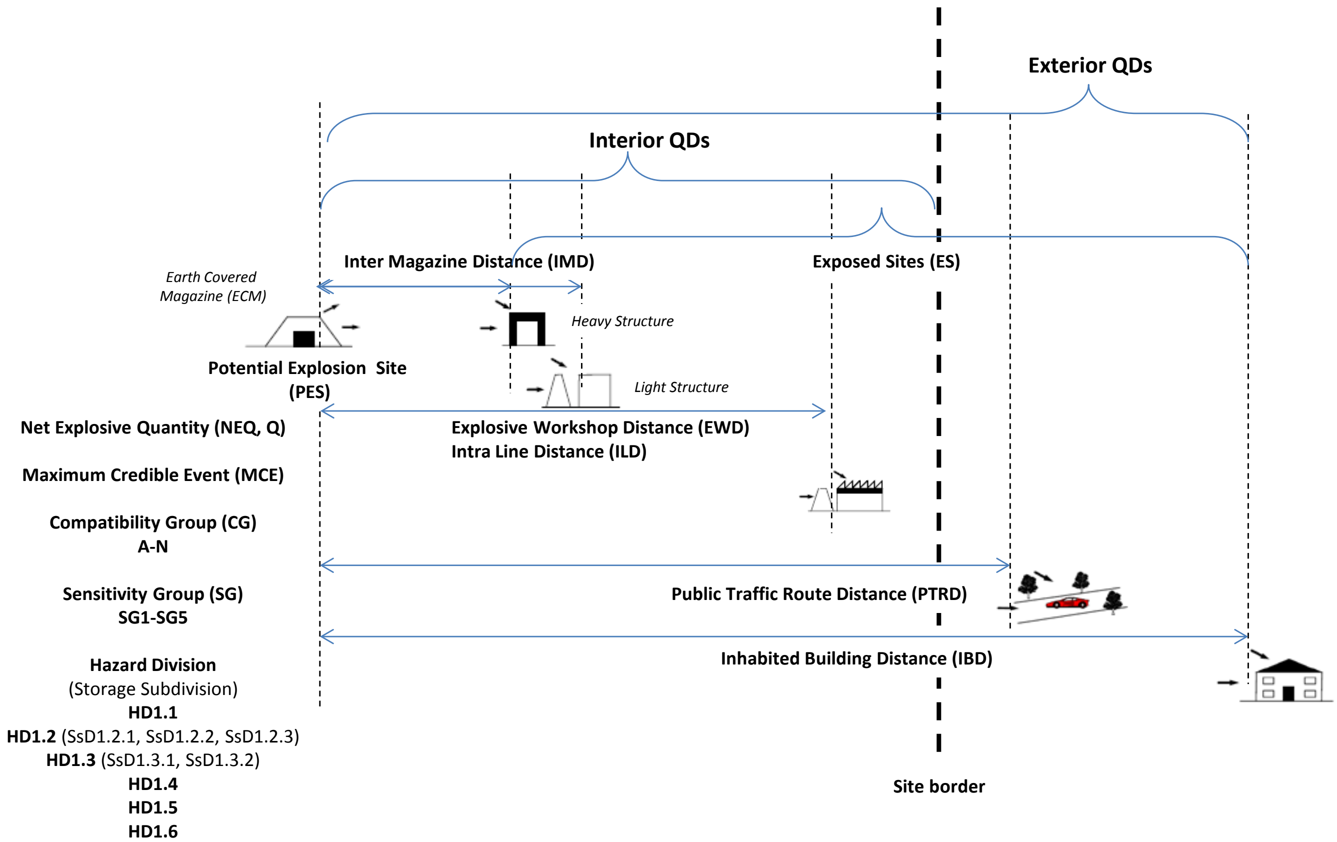
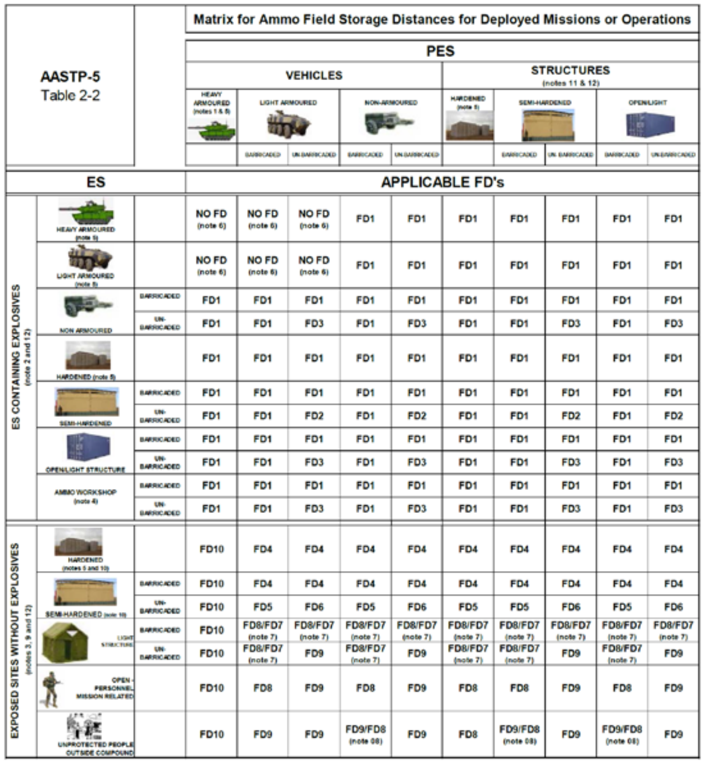


Figure 1. Graphical overview of “QD terminology”

QDs are typically specified for 3 types of PES (Earth Covered Magazines (ECMs), Heavy- and Light above ground magazines) depicted with 10 different pictograms. There are 10 types of ES (ECMs, Heavy- and Light above ground magazines, Explosive Workshops, Public Traffic Routes, Inhabited Buildings, Vulnerable Constructions, Related Offices, Power Grids and POL installations) resulting in 28 variations. Inter Magazine Distances (IMD) provide a level of protection against prompt sympathetic reaction in ES that contain AE. In order to achieve this, all magazines and workshops containing AE have to satisfy the relevant IMDs, both as a PES and as an ES. In some cases QDs are given for multiple protection levels (Virtually complete protection, High degree of protection and Limited protection). QDs for Explosive Workshops and most of the exterior QDs such as Inhabited Building Distance (IBD) and Public Traffic Route Distance (PTRD) are aimed to provide a level of protection to both related and unrelated personnel and third parties. Although there are 280 PES-ES pairs, there are only a limited amount of distinct QD relations. These are provided as equations and in table format. An important future addition to AASTP-1 will be QDs for the storage of Small Quantities of AE [SQQD WP, 2015].

[AASTP-5, 2016] deals with storage of ammunition on deployed missions or operations, and provides Field Distances (FDs). To keep the manual lean and easy to apply, all AE except HD1.4 has to be aggregated as HD1.1. FDs are given for a high protection level only and for NEQ up to 4,000 kg. For larger NEQ the AASTP-1 QDs apply. Figure 2 shows a table from AASTP-5 that links all PES-ES pairs to a prescribed FD. Table 1 gives an overview of the differences between AASTP-1 and AASTP-5.



Matrix for Ammo Field Storage Distances for Deployed Missions or Operations

AASTP-5 Table 2-2

ES			PES: VEHICLES: HEAVY ARMOURED (notes 1 & 5)	LIGHT ARMOURED: BARRICADED	LIGHT ARMOURED: UN-BARRICADED	NON-ARMOURED: BARRICADED	NON-ARMOURED: UN-BARRICADED	STRUCTURES (notes 11 & 12): HARDENED (note 5)	SEMI-HARDENED: BARRICADED	SEMI-HARDENED: UN-BARRICADED	OPEN/LIGHT: BARRICADED	OPEN/LIGHT: UN-BARRICADED
ES CONTAINING EXPLOSIVES (note 2 and 12)	HEAVY ARMOURED (note 5)		NO FD (note 6)	NO FD (note 6)	NO FD (note 6)	FD1	FD1	FD1	FD1	FD1	FD1	FD1
	LIGHT ARMOURED (note 5)		NO FD (note 6)	NO FD (note 6)	NO FD (note 6)	FD1	FD1	FD1	FD1	FD1	FD1	FD1
	NON ARMOURED	BARRICADED	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1
		UN-BARRICADED	FD1	FD1	FD3	FD1	FD3	FD1	FD1	FD3	FD1	FD3
	HARDENED (note 5)		FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1
	SEMI-HARDENED	BARRICADED	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1
		UN-BARRICADED	FD1	FD1	FD2	FD1	FD2	FD1	FD1	FD2	FD1	FD2
	OPEN/LIGHT STRUCTURE	BARRICADED	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1
		UN-BARRICADED	FD1	FD1	FD3	FD1	FD3	FD1	FD1	FD3	FD1	FD3
	AMMO WORKSHOP (note 4)	BARRICADED	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1	FD1
		UN-BARRICADED	FD1	FD1	FD3	FD1	FD3	FD1	FD1	FD3	FD1	FD3
EXPOSED SITES WITHOUT EXPLOSIVES (notes 3, 9 and 12)	HARDENED (notes 5 and 10)		FD10	FD4	FD4	FD4	FD4	FD4	FD4	FD4	FD4	FD4
	SEMI-HARDENED (note 10)	BARRICADED	FD10	FD4	FD4	FD4	FD4	FD4	FD4	FD4	FD4	FD4
		UN-BARRICADED	FD10	FD5	FD6	FD5	FD6	FD5	FD5	FD6	FD5	FD6
	LIGHT STRUCTURE	BARRICADED	FD10	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD8/FD7 (note 7)
		UN-BARRICADED	FD10	FD8/FD7 (note 7)	FD9	FD8/FD7 (note 7)	FD9	FD8/FD7 (note 7)	FD8/FD7 (note 7)	FD9	FD8/FD7 (note 7)	FD9
	OPEN - PERSONNEL MISSION RELATED		FD10	FD8	FD9	FD8	FD9	FD8	FD8	FD9	FD8	FD9
	UNPROTECTED PEOPLE OUTSIDE COMPOUND		FD10	FD9	FD9	FD9/FD8 (note 08)	FD9	FD8	FD9/FD8 (note 08)	FD9	FD9/FD8 (note 08)	FD9

Figure 2. Mapping of PES-ES pairs to Field Distances in AASTP-5.

Table 1. Differences between AASTP-1 and AASTP-5.

	AASTP-1	**AASTP-5**
Application	Static storage	Storage on deployed missions
Terminology	Quantity Distance (QD)	Field Distance (FD)
Number of pages with tables	98	2
Protection levels	Limited, High, Virtually Complete	High
Number of PES (incl. barricades)	10	10
Number of ES (incl. barricades)	28	18
Number of HD1.1 QD/FD relations	17 + 17 (SQQD)	10
Range of NEQ for HD1.1	500 - 250,000 kg 1 – 500 kg (SQQD)	25 – 4,000 kg
Number of HD1.2 QD/FD relations	8	None
Range of NEQ for HD1.2	10 – 500,000 kg	Aggregated as HD1.1
Number of HD1.3 QD/FD relations	4	None
Range of NEQ for HD1.3	500 – 250,000	Aggregated as HD1.1
HD1.4 QD/FD	on firefighting requirements Based	Left out of consideration
HD1.5 QD/FD	Treated as HD1.1	Aggregated as HD1.1
HD1.6 QD/FD	Detonation of single article or burn of total NEQ	Aggregated as HD1.1

The development of the standards took place over many decades by explosives safety experts. The QDs and FDs are based on the analysis of a large number of explosives tests- and accident data. Based on additional testing and analysis accomplished in recent years, a comprehensive and transparent overview of the basis for the QDs is necessary in order to validate them and to eliminate inconsistencies. Such an overview will also help to educate new people in the field.

The Munitions Safety Information Analysis Center (MSIAC) conducted a study on the experimental and theoretical basis of QDs. This paper presents a structured approach to QDs, starting with the amount of munitions involved in the munitions response, and then treating each explosion effect separately. This approach aims to reproduce the standards as closely as possible, but there might be instances where results are not fully consistent. The paper summarizes the results obtained for HD1.1, HD1.2, HD1.5 and HD1.6, i.e. those HDs for which blast, fragmentation and debris typically constitute the main hazards. A more detailed report [van der Voort et al., 2016] as well as a repository of all references will be completed towards the end of 2016.

RESPONSE OF AMMUNITION AND EXPLOSIVES

In this Section we will discuss for each hazard division the NEQ involved in the AE response in relation to the explosion effects. An overview is given in Table 2.

Table 2 Relevant NEQ associated with each explosion effect for HD1.1, HD1.2 (SsD 1.2.1, 1.2.2, 1.2.3), HD1.5 and 1.6.

HD / SsD	**Mass detonation explosion effects**					**HD1.2 fragment effects**		**Thermal effects**
	Blast	*Debris low*	*Debris high*	*HD1.1 Fragments low*	*HD1.1 Fragments high*	*HD1.2 Fragments low*	*HD1.2 Fragments high*	*Thermal*
1.1	Total NEQ	Total NEQ	Total NEQ	Total NEQ	Total NEQ	-	-	Total NEQ
1.2.1 (>0.136 kg/round)	MCE_{121}	MCE_{121}	MCE_{121}	MCE_{121}	MCE_{121}	Total NEQ	Total NEQ	-
1.2.2 (≤0.136 kg/round)	-	-	-	-	-	Total NEQ	Total NEQ	-
1.2.3* (>0.136 kg/round)	NEQ of single article	NEQ of single article	NEQ of single article	NEQ of single article	NEQ of single article	-	-	Total NEQ
1.2.3 (≤0.136 kg/round	-	-	-	-	-	-	-	Total NEQ
1.5	Total NEQ	Total NEQ	Total NEQ	Total NEQ	Total NEQ	-	-	Total NEQ
1.6	NEQ of single article	NEQ of single article	NEQ of single article	NEQ of single article	NEQ of single article	-	-	Total NEQ

*No formal distinction between SsD1.2.3 rounds with an NEQ smaller and greater than 0.136 kg exists. The distinction in this table has been made because of the importance for QD determination.

The overall QD is determined as the maximum of the QDs relevant for the individual explosion effects (each QD determined with its own relevant NEQ as given in Table 2):

$$QD = \max(QD_{blast}, QD_{debris}, QD_{HD11frag}, QD_{HD12frag}, QD_{therm}) \qquad \text{(Equation 1)}$$

For HD1.1 it is generally assumed that a mass detonation takes place that involves the total NEQ present in a PES, resulting in blast, debris, fragments and thermal effects. For debris and fragments we distinguish between low and high angle contributions. This is done for three reasons: low and high angle debris originate from different sources (e.g. wall versus roof), have different impact conditions (e.g. high velocity versus terminal velocity) and can be mitigated by different means (e.g. barricade versus protective roof). HD1.5 is to be treated identical to HD1.1 and therefore has the same entries.

For HD1.2 we distinguish between SsD1.2.1, 1.2.2, and 1.2.3 [HD1.2 WP, 2013]. The distinction between SsD1.2.1 and 1.2.2 is based on the applicable High Explosive (HE) content per round, which may differ from the NEQ. The HE content rather than the NEQ is used, as this is what “generates the primary fragments of concern with the highest velocities and greater range". The upper limit for SsD 1.2.2 was set at 0.136 kg HE/round, which is related to external fire tests with the German 40 mm DM31 round. All rounds with a larger HE content are grouped in SsD1.2.1, for which the QDs are based on trials with 81 mm mortar rounds and 105 mm artillery rounds [Swisdak et al., 1998].

SsD1.2.3 QD is based on the NEQ of the largest single round present, taking into account the insensitiveness of SsD1.2.3 munitions to specific external stimuli. It exhibits at most an explosion reaction in sympathetic reaction testing, and a burning reaction in bullet impact, slow heating, and liquid fuel /external fire testing as described in [AOP-39, 2010].

Besides the projection hazard, which persists over longer periods of time (minutes, hours), HD1.2 may also exhibit "HD1.1-like" behavior. This happens when multiple munitions explode (nearly) simultaneously, not necessarily with a causal relation. This behavior can cause a limited blast, debris and fragment hazard. The Maximum Credible Event (MCE) is defined as the maximum NEQ that is involved in this "mass" detonation. For SsD1.2.1 the MCE can be determined in one of three ways.

- Munitions that produce fragmentation effects similar to 81 mm and 105 mm, as tested in the NATO HD 1.2 Test Program, can be considered to have a default MCE with a maximum of 50 kg (MCE_{121} = 50 kg HD1.1).
- Established by testing, analogy, or available data (MCE_{121} up to 500 kg HD1.1)
- HE content of three unpalletised outer shipping packages (MCE121 up to 500 kg HD1.1)

An additional limitation is that the MCE will never be larger than the total NEQ stored in the magazine. This might be relevant for storage of very small quantities of SsD 1.2.1.

For SsD1.2.2, due to its small HE content per round, the MCE is not a consideration. For SsD1.2.3 the MCE is assumed to be the NEQ of a single article or package as determined through testing. Logically speaking this only applies to those SsD1.2.3 items with more than 0.136 kg HE/round. The MCE for HD1.6 is based on the detonation of a single article. The approach for SsD1.2.3 and HD1.6 differs slightly in the way the MCE is quantified. This is not further discussed in the current paper.

For SsD1.2.3 and HD1.6 the MCE has to be compared to a burn of the total NEQ. For large stacks the thermal effects will determine the QD. AASTP-1 provides a HD1.6 QD table for a unit load of 1,000 kg. This presumably serves as an example, but may lead to the confusion that this table is to be used for all HD1.6 ammunition. An allowance is permitted to treat SsD 1.2.3 as either SsD 1.2.1 or SsD 1.2.2, as applicable (based on explosive content) to ensure that SsD 1.2.3 QD never exceeds that of SsD 1.2.1 or SsD 1.2.2, which would be extremely conservative and contrary to the goals for encouraging the development of SsD 1.2.3 munitions.

BLAST

Introduction

The first explosion effect to be discussed is blast. AASTP-1 assumes that blast from a Hemispherical Surface Burst (HSB) is representative for all PES, except for the side and rear of an ECM for which attenuation is taken into account. Blast reduction due to PES and ES barricades is neglected in most cases. In this section we will discuss blast scaling, and the background of the various QDs and FDs that are (primarily) based on blast.

Blast scaling

A well validated state of the art model for the prediction of blast wave propagation from a HSB is described in [DDESB TP17, 2016] and [AASTP-4, 2016]. This model provides blast wave parameters like the side-on peak overpressure (P) and scaled side-on impulse ($i/Q^{1/3}$) as a function of scaled distance ($Z = R/Q^{1/3}$), with R the distance to the center of the charge. This is illustrated in Figure 3.

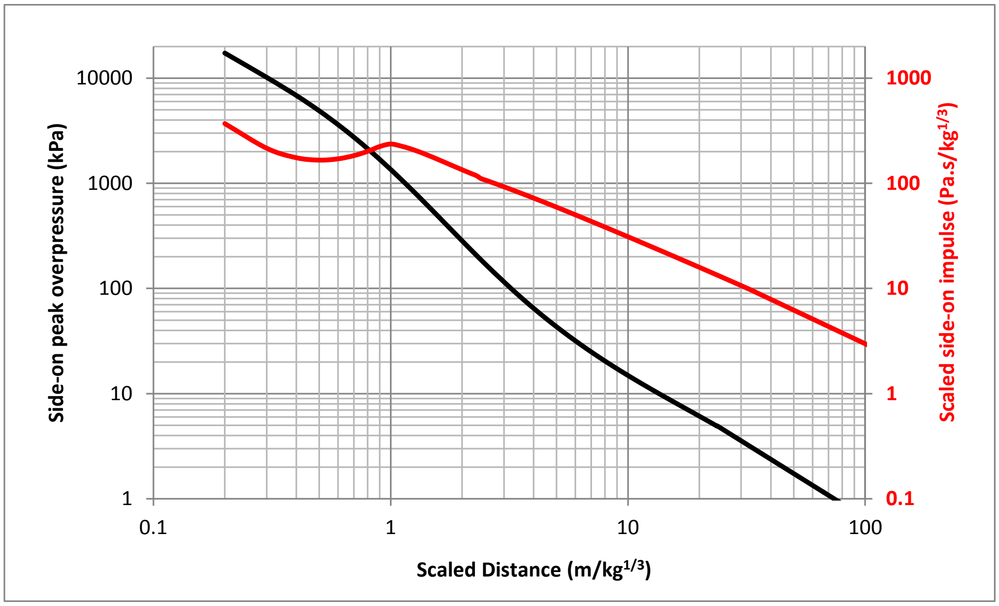


Figure 3. The side-on peak overpressure and scaled side-on impulse as a function of scaled distance for a hemispherical surface burst

When a QD is to be based on a blast overpressure criterion, the model shows that for all overpressure levels the QD follows a 1/3 power law:

$$QD_P = Z \cdot Q^{\frac{1}{3}} \qquad \text{(Equation 2)}$$

A striking difference occurs when a QD is to be based on blast impulse. In this case a simple scaling rule exists for $1 < Z < 100$ m/kg$^{1/3}$ (Figure 3). In this region the scaled impulse falls off as approximately 1 over the scaled distance:

$$I/Q^{\frac{1}{3}} \sim \frac{1}{R/Q^{\frac{1}{3}}} \qquad \text{(Equation 3)}$$

Setting R equal to QD_I leads to a 2/3 power law, with C a constant:

$$QD_I = C \cdot Q^{\frac{2}{3}} \qquad \text{(Equation 4)}$$

Overview of HD1.1 Blast QDs and FDs

Table 3 gives an overview of all QDs and FDs that are based on a 1/3 power law. The application ranges from protection against prompt sympathetic reaction (IMD), a specified level of building damage (e.g. EWD, PTRD, IBD) and blast injury. In the case of IMDs we note that blast is often not the only relevant explosion effect. Close-in to the explosion the combination of multiple explosion effects has to be considered which includes cratering, ground shock, launched debris and barricade material. It has however been assumed a priori that all IMDs follow a 1/3 power law. Table 3 shows that many values of Z are simultaneously used as QD, SQQD and FD, although the range of NEQ differs. These instances are shown in red. The addition “part’’ indicates that the Z value changes to another value within the relevant range of NEQs. The addition “imp” indicates that the QD transitions to an impulse criterion (2/3 power law) for small NEQ. The side-on peak overpressure is shown in case it has been explicitly mentioned in AASTP-1 or AASTP-5, or supporting documents.

Table 3. Overview of all HD1.1 QDs, SQQDs, and FDs that follow a 1/3 power law. The side-on peak overpressures that are mentioned in the standards as well as the application are mentioned. *The details refer to damage levels specified in Table 4.

Z ($m/kg^{1/3}$)	**P_s (kPa)**	**AASTP-1**		**AASTP-5**	**Application**	**Details**
		QD	***SQQD***	***FD***		
0.35	-	D1 part			IMD	between barricaded open stacks of bombs
0.4	-			FD1 part	IMD	between barricaded ISO containers
0.44	-	D2 part			IMD	between barricaded open stacks of bombs
0.5	-	D3	SQ1		IMD	between any combination of ECM rear and side walls
0.6	-			FD1 part	IMD	between barricaded ISO containers
0.8	-	D4	SQ2		IMD	between ECM front and ECM rear
1.1	-	D5	SQ3		IMD	between ECM front and ECM side
1.8	-	D6	SQ4		IMD	between ECMs not meeting requirements
2.4	-	D7	SQ5	FD2	IMD	between ECMs not meeting requirements between unbarricaded semihardened
3.6	-	D8			IMD	between ECM front and ECM front
4	65			FD4	Inhabited Field Structure	lung injury in hardened structure
4.8	-	D9	SQ6	FD3	IMD	between ECMs not meeting requirements (front to front), building damage level A* due to blast from HSB between unbarricaded open/light for storage of robust ammunition
6	32			FD5	Inhabited Field Structure	lung injury in semi-hardened structures
7.2	24	D10(US)			EWD in US	building damage level B* due to blast from HSB
8	21	D10	SQ7	FD6	EWD	building damage level Cb-B* due to blast from HSB
11.1	-		SQ8		PTRD	building damage level Cb-B* due to blast from HSB
13	10			FD7 part	Inhabited Field Structure	light structure damage
14.8	9	D11 imp			PTRD	building damage level Ca-Cb* due to blast from HSB
22.2	5	D12/ D13 imp	SQ9 SQ11,12,13 part	FD10 part	IBD	building damage level Ca* due to blast from HSB
44.4	2	2*D12/ 2*D13 imp	SQ10		Vulnerable Constructions	building damage level D due to blast from HSB
9.3	9	D16			PTRD	building damage level Ca-Cb* due to blast from ECM rear
12	9	D17			PTRD	building damage level Ca-Cb* due to blast from ECM side
14	5	D14			IBD	building damage level Ca* due to blast from ECM rear
18	5	D15			IBD	building damage level Ca* due to blast from ECM side

28	2	2*D14			Vulnerable Constructions	building damage level D* due to blast from ECM rear
36	2	2*D15			Vulnerable Constructions	building damage level D* due to blast from ECM side

<u>QDs based on building damage due to blast from HSB</u>

Observation of damage to brick houses after the WWII London bombings led to the following equation for the Average Circle Radii (ACR) for a number of damage levels [Jarrett, 1968], [Gilbert et al., 1994]:

$$ACR = \frac{RB \cdot k_{ACR} \cdot Q^{\frac{1}{3}}}{\left[1 + \left(\frac{Q_{ACR}}{Q}\right)^2\right]^{\frac{1}{6}}} \qquad \text{(Equation 5)}$$

Eq. 5 contains the following constants: k_{ACR} = 7.1 m/kg$^{1/3}$ and Q_{ACR} = 3,175 kg. Table 4 provides various details on the damage levels. RB is the ratio of the ACR for a particular damage level to the ACR of damage level B. In the Dutch Green Book [PGS1-2B, 2003] the damage levels are also presented in terms of peak overpressure and impulse. [Gilbert et al., 1994] have provided estimates of the probability of lethality, and serious- and light injury. It should be noted that the model is valid for housing in the WWII era: 1900 - 1940 style brick houses, single leaf walls, wooden floors and roof, 2 to 4 storeys high.

The ACR has been plotted in Figure 4 for all damage levels. In the remainder of this paper these are referred to as the “Jarrett-curves”. It can easily be seen that for large Q (>4,500 kg), Eq. 5 reduces to a $Q^{1/3}$ (pressure) scaling. This is the quasi-static (step load) regime. For small Q (<2,500 kg), Eq. 5 reduces to a $Q^{2/3}$ (impulse) scaling, which corresponds to the impulsive regime. The transition is called the dynamic regime which may be approximated by a $Q^{1/2}$ scaling.

Table 4. Building damage levels, RB ratio, side-on overpressure and impulse criteria, description, and probability of injury (K=kill, SI= serious injury, LI=light injury). Based on [Gilbert et al., 1994] and [PGS 1-2B, 2003].

Damage level	**RB ratio**	**P (kPa)**	**I (Pa.s)**	**Description**	**Injury (%)**		
					P(K)	**P(K+SI)**	**P(K+SI+LI)**
A	0.675	47	905	almost complete demolition	56.6 to 95.5	66.4 to 100	81.5 to 100
B	1.00	24	588	50-75% external brickwork destroyed or rendered unsafe and requiring demolition	8.6	15.2	38
Cb	1.74	11	350	houses uninhabitable – partial or total collapse of roof,partial demolition of one to two external walls,severe damage to load-bearing partitions requiring replacement	0.9	4.3	13
Ca	3.0	5.6	222	not exceeding minor structural damage,and partitions and joining wrenched from fittings	0	0.2	0.6
D	6.0	2.2	118	remaining inhabitable after repair – some damage to ceilings and tiling,more than 10% window panes broken	0	0	0

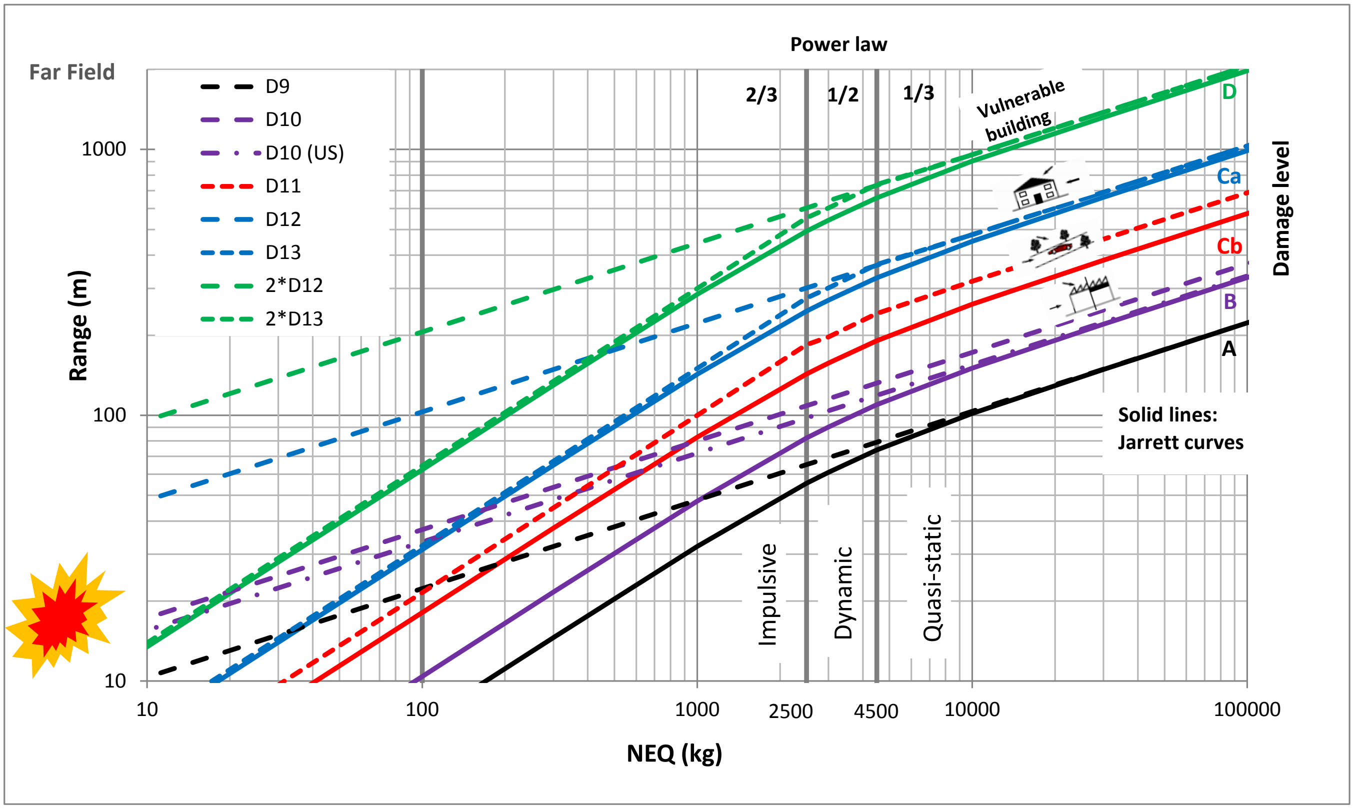


Figure 4. ACR to various damage levels (solid lines) plotted together with a number of HD1.1 Blast QDs from AASTP-1 (dashed lines).

Figure 4 also shows a number of HD1.1 blast QDs. D9 through D13 are clearly related to the Jarrett curves, and are in fact approximations. The PTRD (D11) and IBD (D13) are both formulated as a combination of functions for each of the three loading regimes.

Table 5 Equations for D11 and D13

Formula	Q ≤ 2500 kg	2500 < Q ≤ 4500 kg	Q > 4500 kg
D11	$1 \cdot Q^{\frac{2}{3}}$	$3.6 \cdot Q^{\frac{1}{2}}$	$14.8 \cdot Q^{\frac{1}{3}}$
D13	$1.5 \cdot Q^{\frac{2}{3}}$	$5.5 \cdot Q^{\frac{1}{2}}$	$22.2 \cdot Q^{\frac{1}{3}}$

An important observation from Figure 4 is that D13 is based on damage level Ca (negligible lethality), while the PTRD (D11) is related to a damage level close to Cb (1% lethality). As a rule of thumb the ratio between PTRD and IBD is 2/3. Another observation is that the QD for vulnerable constructions (2*D12 or 2*D13) is based on damage level D.

D9, D10 and D12 do not exploit the behavior in the impulsive loading regime, which leads to a conservative approach for small NEQ. The EWD (D10) exists in two variants; the one used in the US corresponds to severe damage level B (8.6% lethality), the other to a somewhat less severe damage.

<u>FDs based on building damage due to blast from HSB</u>

AASTP-5 has devoted FD7 to prevent damage to light structures (containers) typically used by personnel during deployed missions [Anderson et al., 2008]. FD7 is based on a generic peak overpressure value of 10 kPa above 500 kg HD1.1. Below 500 kg a 1/2 power law is used.

QDs based on building damage due to blast from ECM side and rear

[DDESB TP17, 2016] and [AASTP-4, 2016] also provide models for blast from the front, side, and rear of ECMs. These are compared to the HSB model in Figure 5. Close-in to the PES the peak overpressures from the side and rear of an ECM are significantly attenuated relative to the HSB. At the front of the ECM the peak overpressure is initially slightly larger than the HSB, but drops in the far field to a level comparable to the side of the ECM.

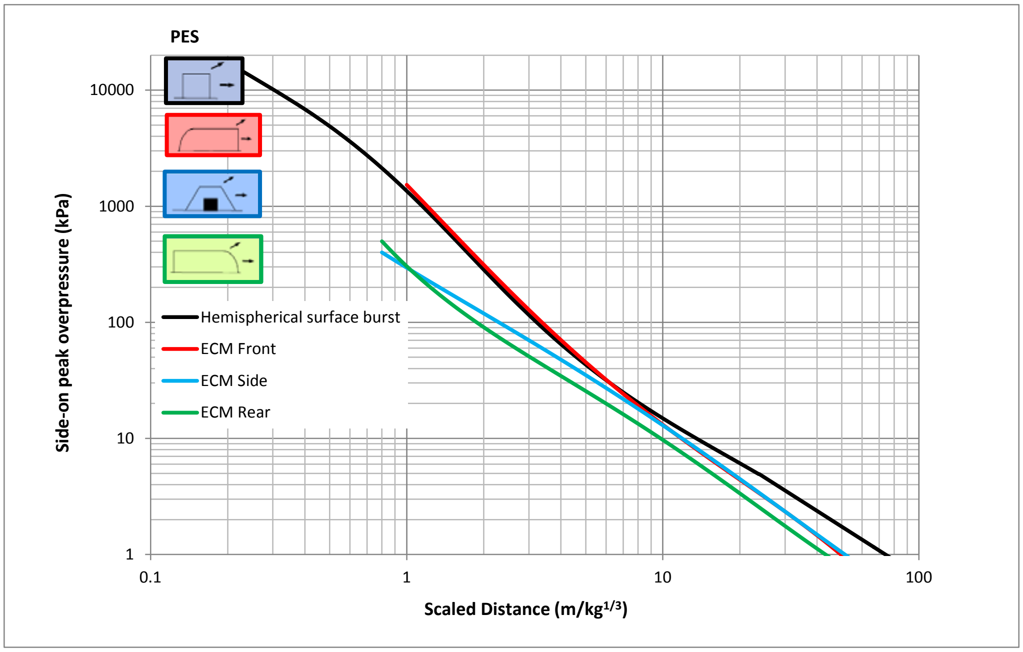


Figure 5. The side-on peak overpressure as a function of scaled distance for a HSB, and for the front, side and rear of an ECM.

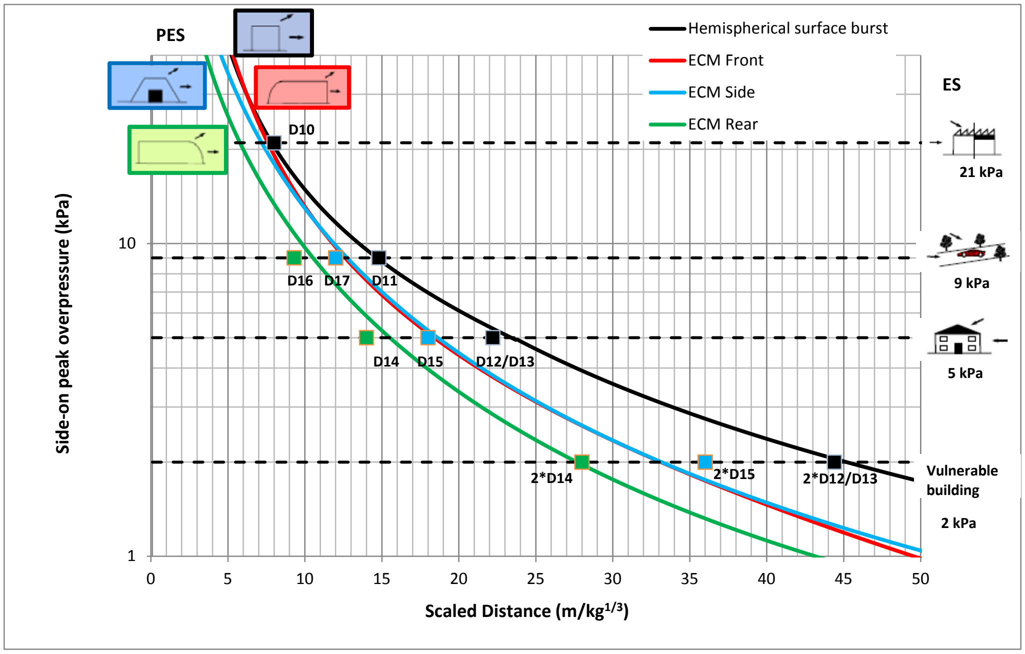


Figure 6. The side-on peak overpressure as a function of scaled distance for a HSB, and for the front, side and rear of an ECM.

Figure 6 shows a comparison between the various blast predictions and all AASTP-1 QDs related to building damage due to blast. D9 through D13 show a good agreement with the HSB peak overpressures. D14 through D17 correspond well to peak overpressures from the rear and side of an ECM. In analogy to the case for HSB, there is again a factor 2/3 between PTRD (D17) and IBD (D15), and between PTRD (D16) and IBD (D14). In AASTP-1 no attenuation is taken into account for blast from the front of an ECM, which is a conservative approach.

<u>IMDs</u>

[QD Criteria for above ground storage, 2013] briefly describes the background of the IMDs in AASTP-1. Not all references mentioned in that document were currently available, which will be indicated as Not Available (**NA**). For this reason not all IMDs could be traced back to their origin. Also the rationale behind the application of some IMDs to certain PES-ES combinations is not always clear. Some of the available information is repeated below and additions have been made.

Barricaded open stacks: D1 and D2

D1 ($0.35 \cdot Q^{1/3}$ for NEQ < 30,000kg) and D2 ($0.44 \cdot Q^{1/3}$ for 30,000 < NEQ < 120,000 kg) prevent sympathetic detonation between barricaded open stacks of aircraft bombs. These QDs are based on the UK ESTC Soltau trials [**NA**, 1947] and the US Big Papa test [Petersen et al., 1968]. The latter reference describes a test with a donor and multiple acceptor stacks consisting of tritonal-filled M66A2 and M117 bombs. The test layout is shown in Figure 7. Two acceptors were located at D2, a third at D1, and the fourth at $1 \cdot Q^{1/3}$. In a second test (phase 2) two acceptors were again placed at D2, with a third even closer (at $0.32 \cdot Q^{1/3}$). From these tests it was concluded that the minimum barricaded distance between single stacks of mass-detonating explosives stored in adjacent cells of a module could be based on D2 with a high degree of confidence since six stacks, located at distances D2 or less were tested without causing any sympathetic simultaneous or delayed detonations. Bombs located at D2 or less will be covered with earth as a result of a detonation at an adjacent cell and will be unavailable for use until extensive uncovering operations are completed. Bombs located at a minimum distance of $1 \cdot Q^{1/3}$ will be readily accessible.

Some damage to bombs and occasional fires or delayed explosions may however occur. The use of D2 is limited to situations not involving combustible materials and when stored within only lightweight weather protection (i.e. metal shed roof or tarpaulin), to prevent delayed propagation by fire.

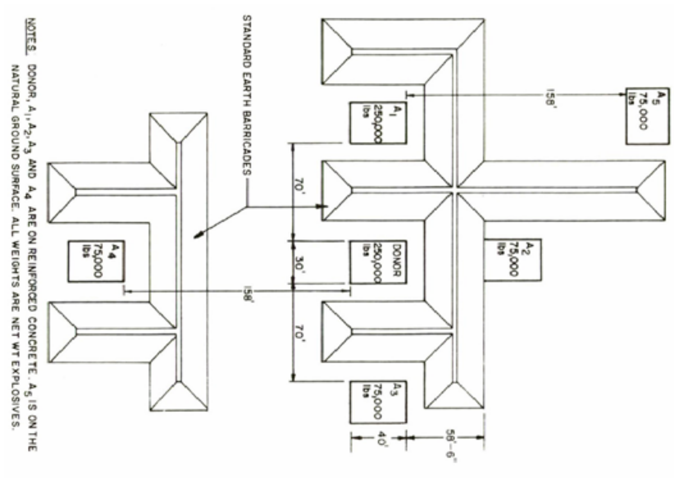


Figure 7. Layout of phase I of the Big Papa test [Petersen, 1968]. The NEQ for the donor and five acceptors as well as their separation distances are indicated in US units.

Barricaded ISO containers: FD1

FD1 consists of two parts: $0.4 \cdot Q^{1/3}$ for NEQ < 1,500 kg, and $0.6 \cdot Q^{1/3}$ for 1,500 kg < NEQ ≤ 4,000 kg. FD1 is comparable to D1 and D2, but is based on test configurations with ISO containers and barricades typical for deployed missions and with smaller NEQ. The various tests from the US, Canada, Denmark, Germany and the Netherland, are described by [Anderson et al., 2008].

An example is the 5 tonnes trial conducted in Woomera in 2002, which involved the detonation of 299 M106C1 shells in an ISO container. Four barricaded acceptor containers with various types of live and inert munitions were placed around the PES at scaled distances of 0.5 and $0.8 \cdot Q^{1/3}$ (Figure 8). Although the acceptor containers were heavily damaged, no reaction of the live munitions took place [Van Wees et al., 2004]. Note that the ES contained Sensitivity Group 5 (SG 5) detonators and plastic explosives.

Figure 8. Layout of the 5 tonnes trial in Woomera, 2002 [Van Wees et al, 2004].

ECMs: D3, D4, D5

ECMs are required to have at least 60 cm of earth cover on the roof and follow a 2:1 slope at the sides and rear. D3 ($0.5 \cdot Q^{1/3}$), D4 ($0.8 \cdot Q^{1/3}$), and D5 ($1.1 \cdot Q^{1/3}$) can be applied for ECMs which have a headwall and door(s) designed for external overpressures of 7 or 3 bars (except for front exposed 3 bar ECMs). AASTP-1 mentions a number of additional design requirements.

D3 applies to any combination of rear- or side walls of 7 or 3 bar ECMs. In these cases the headwall and doors of the acceptor ECM are exposed to a side-on blast load from an explosion at the PES. D3 should not be used in wet sand or wet clay which is associated with unusually large crater size and ground shock effects.

D4 applies when the front of an ECM faces the rear of another. D5 applies when the front of an ECM faces the side of another. In both cases the head wall and door of the acceptor ECM would be exposed face-on to the blast from an explosion at the PES. D4 and D5 are however also prescribed in the opposite direction; when the donor is an ECM with its front facing the rear or side of an acceptor ECM.

The origin of these QDs goes back to the Eskimo magazine separation test. The layout of Eskimo I [Weals, 1973] is shown in Figure 9 (left). The donor ECM contained 155 mm projectiles with an NEQ of 200.000 lb (about 90.000 kg). Four acceptor ECMs were placed at D3 (east), D4 (south and north), and D5 (west). [Weals, 1973] describes that in each acceptor ECM eight high-explosive charges were placed in two rows across the face of the magazine.

The doors of the acceptors at D4 and D5 were pushed inwards, but no explosion or burning occurred. In the acceptor at D3 the charges reacted and caused major damage. Based on these results the US DDESB authorized D4 for face to rear exposures and D5 for face to side exposures.

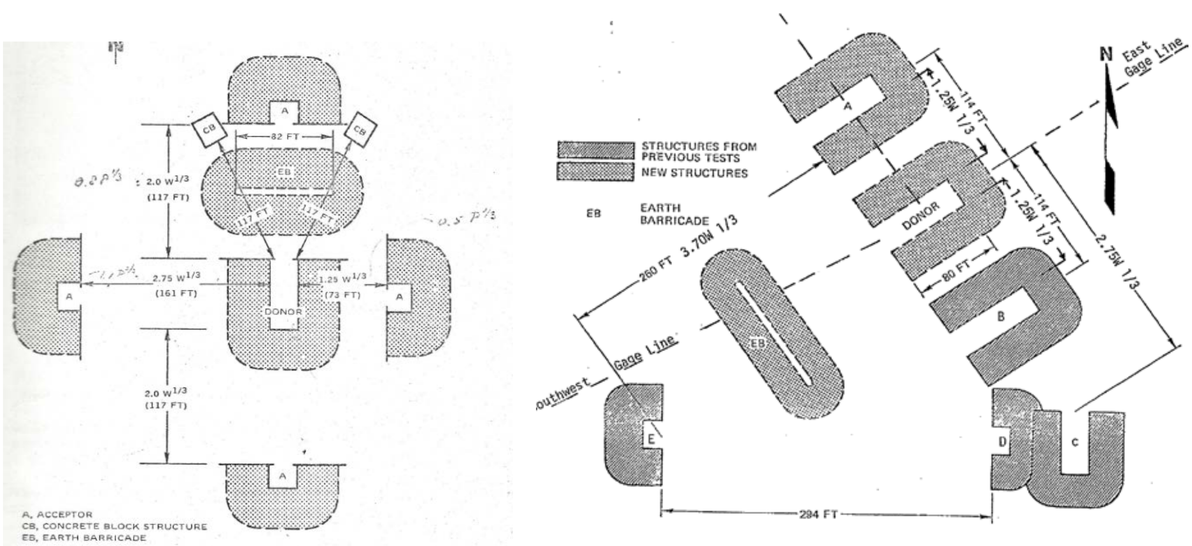


Figure 9. Layout of the Eskimo I magazine separation test [Weals, 1973] (left), and Eskimo III test [Zaker, 1976] (right). Separation distances and charge weights in US units.

In the Eskimo II test [Weals, 1974] various door and headwall combinations were tested. A single leaf sliding door withstood the blast well, and can be expected to provide a high level of protection to stored ammunition. Eskimo III validated the use of D3 for side to side exposures [Zaker, 1974].

ECMs: D6 and D7

When requirements for the design of ECM head-wall and doors are not met, D3, D4 and D5 are replaced by D6 ($1.8 \cdot Q^{1/3}$) and D7 ($2.4 \cdot Q^{1/3}$). The rationale for these QDs is currently unavailable. With respect to

D6, it is mentioned that it prevents propagation of an explosion when the walls of the ES are Reinforced Concrete (RC) at least 25 cm thick. For D7, reference is made to the French Burlot tests [**NA**, 1985].

ECMs: D8 and D9

D8 ($3.6 \cdot Q^{1/3}$) applies to front to front exposures of 3 and 7 bar ECMs. AASTP-1 indicates that for this situation high velocity projections are the primary hazard. When requirements for the design of the head-wall and doors are not met, D8 is replaced by D9 ($4.8 \cdot Q^{1/3}$). D9 corresponds to building damage level A for relatively weak brick buildings, as mentioned before.

ECM blast load comparison

Figure 10 compares the aforementioned IMDs for side and rear exposed ECMs (7 bar, 3 bar and undefined), with TP17 blast predictions. For these exposures the head wall is exposed by a side-on blast load. Due to the limited validity of TP17 for small scaled distances it is not always possible to verify the blast load. Generally speaking the TP17 blast predictions have a tendency towards peak overpressures that exceed the design criteria. For frontally exposed ECM we would need to compare the IMDs with a reflected blast load, which has been omitted in the current paper. [Nationally Approved Structures, 2010] contains an overview of measured head wall blast loads recorded in the aforementioned Eskimo trials and scaled ECM tests from the UK. A list of ECM designs approved for new construction can be found in [DDESB TP15, 2010] and [WBDG, 2016]. For each design DDESB specifies the maximum allowable NEQ that can be stored in an adjacent ECM at the IMD for a specific orientation. This has been based on analysis or testing up to a blast impulse of that NEQ at the IMD.

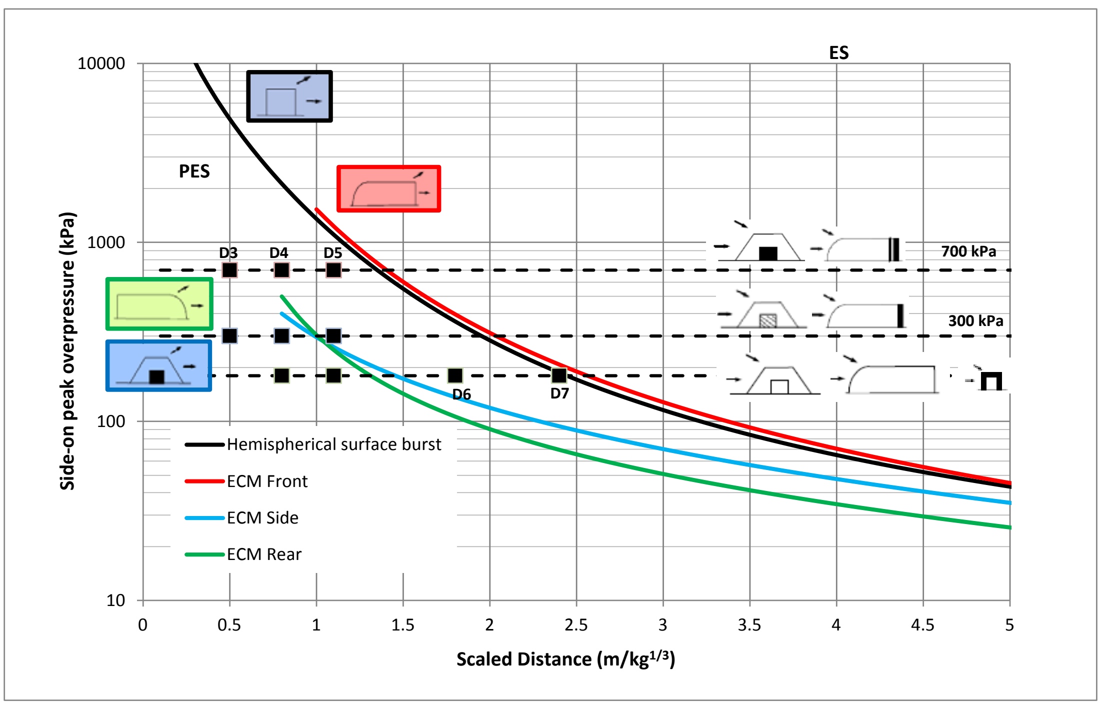


Figure 10. The side-on peak overpressure as a function of scaled distance for a HSB, and for the front, side and rear of an ECM. IMDs for side and rear exposed ECMs are also shown together with design criteria.

Other PES and ES: D7 and D4

For many other PES-ES combinations options are given as in Figure 11. This is relevant for all cases where low angle debris and fragments from the PES are defeated by barricades, but the ES is vulnerable to blast (most light storage magazines). The application of D4 has severe restrictions (no primary explosives and no items vulnerable to spall). [Van Wees et al., 2006] investigated the spalling effects at D4 by exposing a Modular Ammunition Magazine (MAM) with 19 cm RC walls to the blast from 5,000 kg Hexolite (≈ 6,000 kg TNT) at 17 m. The test showed that at D4 "spall" means the collapse of a part of the wall which will impact the acceptor ammunition.

This highlights the necessity not to store ammunition with Sensitivity Group 5 (SG 5) at D4 distances in structures that cause "spall".

D4
High degree of protection
1.3.3.5 No primary explosives
1.3.5.3 No items vulnerable to spall
or D7
High degree of protection

Figure 11. Two options for the IMD towards ES which are protected by barricades from debris and fragments (D4 and D7), but are vulnerable to blast (left). Wall collapse of a Modular Ammunition Magazine at D4 [Van Wees et al., 2006].

Small Quantities (Q ≤ 50 kg)
For small quantities of HD1.1 (Q ≤ 50 kg) most of the IMDs are set to "No QD" [SQQD WP, 2015]. Although the PES may still break up it is assumed that combined explosion effects will not be sufficient to cause sympathetic reaction in adjacent PES. The debris effects for Q ≤ 50 kg are still taken into account for other QDs; this will be discussed in the "debris and fragment" section.

The same assumption has been made for the MCE defined for HD1.2; also in this case most IMDs have been set to "No QD" for MCE ≤ 50 kg. It is important to note that this 50 kg limit coincides with the "default MCE" definition for munitions similar to 81 mm and 105 mm [HD1.2 WP, 2013].

FDs based on lung injury due to blast from HSB
AASTP-5 has devoted two FDs to prevent the onset of lung injury due to blast [Anderson et al., 2008]. This is to address personnel in hardened (FD4) and semi-hardened structures (FD5). Because all other explosion effects are mitigated for these cases, loading of the human body after ingress of a blast wave into the structure is the only hazard that remains. Based on animal testing, [Bowen, 1968] defined a side-on peak overpressure threshold for the onset of lung injury equal to 10 psi (about 65 kPa). Full scale blast tests of hardened structures with a so-called flow-through design (Figure 12) showed a reduction of peak overpressures by 50% [Scherbatiuk, 2005]. On the other hand coalescence of blast waves is known to increase the blast load. The value of 65 kPa ($Z = 4\ m/kg^{1/3}$) was chosen for FD4, while 32 kPa ($Z = 6\ m/kg^{1/3}$) was selected for FD5.

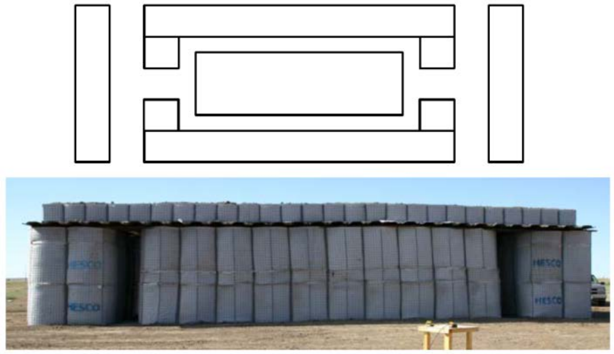


Figure 12. Hardened structure with a flow-through design [Anderson, et al., 2008]

DEBRIS AND FRAGMENTS FROM MASS DETONATION EVENTS

<u>Introduction</u>

After a detonation with sufficient magnitude the walls of a PES will break-up into debris and accelerate. The debris hazard is an important phenomenon for PES such as ISO containers, brick and RC structures, and ECMs. Figure 13 gives an illustration of the directional nature of the debris hazard in a side and a top view during and after two different explosion tests.

Experimental and theoretical work to quantify the debris hazard is conducted within the Klotz Group; a cooperation of 8 nations (Norway, The Netherlands, USA, UK, Singapore, Germany, Switzerland and Sweden). This has led to the Klotz Group Engineering Tool (KG-ET), the theory of which is described by [Van der Voort et al., 2013].

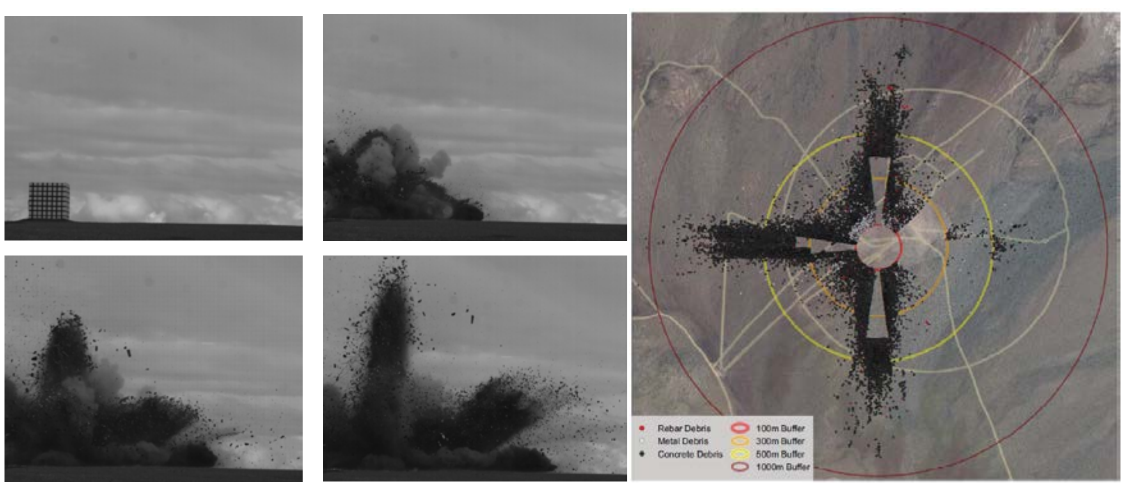


Figure 13. Left: side view of debris throw after detonation of 6.9 kg TNT equivalent in an 8 m^3 RC Kasun structure [Grønsten et al., 2009]. Right: top view of debris throw pattern after detonation of 3,000 kg TNT equivalent in a 250 m^3 RC structure [Anderson et al., 2015].

The break-up process and the launch of debris depends on NEQ, internal volume, and structural properties of the PES. Primary fragments perforate PES ISO container walls and ordinary doors without notable reduction in velocity. Most fragments will not perforate brick and RC walls, but become part of the debris cloud after break-up of the wall. The combined velocity of debris and fragments is close to the debris velocity that would have been obtained with a bare charge, i.e. without fragments. Earth cover adds mass to the walls and roof and influences break-up and venting. As a result velocities and impact distances of debris and fragments will be reduced.

A properly designed PES or ES barricade will stop impacting low angle debris and fragments. Debris just flying over the barricade may still reach large distances. Requirements for PES barricades were recently updated [AASTP-1 Barricade WP, 2016]. To avoid prompt propagation in an adjacent PES, the barricade height must extend 0.3 m above the line of sight from one stack to the other (Figure 14).

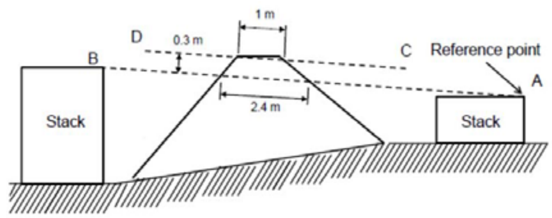


Figure 14. Barricade requirements [Barricade WP, 2016].

Most low angle debris and fragments are defeated by ES brick and RC walls, ECM side and rear earth cover, ECM front barricades, as well as by 3 and 7 bar doors of ECMs. High angle terminal velocity debris and fragments are defeated by protective roofs, while ISO container roofs offer some protection from perforating debris and fragments. Doors of ammunition magazines pose a special threat: although the door represents only one or just a few large pieces of “debris”, the size, mass and potential impact distance make it a relevant object to take into account [Van der Voort et al., 2015].

In this section we will discuss debris scaling, and the background of the various QDs and FDs that are based on debris and fragments.

Scaling of Debris and Fragment QDs

A scaling law for debris distances can be derived from a combination of two equations. The first one is the semi-empirical Debris Launch Velocity (DLV) equation, which was based on a large test program [Dörr et al., 2002]. It predicts the velocity of a slab with areal mass *m* (kg/m^2) launched from a cubicle detonation chamber with internal volume *V* (m^3).

$$DLV = 525 \cdot \sqrt{\frac{Q}{m \cdot V^{2/3}}} \qquad \text{(m/s)} \qquad \text{(Equation 6)}$$

A number of variations to the initial test setup were investigated by [Van Doormaal et al., 2003]. Examples are rectangular geometries and the launch of multiple slabs versus one. This yielded a number of correction factors, but the basic dependencies in Eq. 5 remained.

The second equation is an analytical solution to the equations of motion for a slab moving through air [Van der Voort et al., 2013]. It predicts the impact distance for a launch from ground level with a low angle trajectory. For a fixed launch angle and drag coefficient the equation reads as follows (the *C*’s are constants):

$$R = C_1 \cdot m \cdot \ln\left(1 + \frac{C_2 \cdot DLV^2}{m}\right) \qquad \text{(m)} \qquad \text{(Equation 7)}$$

Substitution of Eq. 5 into Eq. 6 leads to:

$$R = C_1 \cdot m \cdot \ln\left(1 + \frac{C_3 \cdot Q}{m^2 \cdot V^{2/3}}\right) \quad \text{(m)} \qquad \text{(Equation 8)}$$

For a specific building, *m* and *V* are fixed. If *Q* is sufficiently large, $R \sim ln(Q)$; the impact distance scales with the natural logarithm of the NEQ. Although the ballistic behaviour of a debris cloud will differ from a slab, the above scaling does give a heuristic explanation of why many of the debris and fragment QDs are datafits consisting of natural logarithms.

Experimental procedure and definition of debris QDs

The debris (or fragment) IBD is defined as the distance beyond which the hazardous debris density drops below 1/55.7 m^2. Hazardous debris is defined as having an impact energy greater than 79 J, which will typically only lead to lethality for impact at head and thorax [AASTP-4, 2016]. Assuming an impact at terminal velocity, the limiting mass for a hazardous piece of debris equals 90 g for a concrete sphere.

Experimental procedures for debris collection and determination of the IBD are described in [DDESB TP21, 2007]. Three methods exist to determine the hazardous debris density and the IBD. In explosion tests debris is picked up and registered either by applying a radial grid or by GPS. The Actual Debris Density (ADD) is obtained when the number of debris collected in a sector is divided by the sector area. This approach ignores all debris that landed further away, and is therefore not conservative. The Pseudo-Trajectory Normal (PTN) method accounts for all debris that landed in further radial sectors, while the Modified Pseudo-Trajectory Normal (MPTN) method takes 1/3 of these pieces into account. The PTN and MPTN approaches take away the concerns mentioned above, but also introduce a grid dependency. [Anderson et al., 2015] showed that at least for NEQ up to 500 kg, the obtained debris IBDs are not very sensitive to the debris density definition used. IBDs presented in the remainder of this paper have been determined using the PTN method.

The debris hazard is strongly directional and may vary stochastically from one test to another. It is important to realize that the debris IBD is based on average test results in the wall normal direction (the direction perpendicular to the walls).

Overview of HD1.1 debris and fragment QDs and FDs

In [AASTP-1, 2015] the debris hazard is taken into account by application of fixed minimum distances (e.g. 400 m). In analogy to blast, the PTRD is set equal to 2/3 times the IBD. For vulnerable constructions the blast QD is 2 times the blast IBD, however for debris the fixed minimum distance is the debris IBD itself, rather than 2 times the debris IBD. The fixed minimum distances result in overly conservative QDs for small quantities of HD1.1 and SsD1.2.1. A major improvement planned for a new version of AASTP-1 is the addition of debris and fragment-based QDs for small quantities (< 500 kg) of HD1.1 [SQQD WP, 2015]. Table 6 gives an overview of all QDs and FDs that are based on debris and fragments.

Table 6. Overview of all HD1.1 debris and fragment QDs and FDs. For a number of variables equations are provided.

AASTP-1 SQQD	**AASTP-5 FD**	**Equation**	**Application**	**Details**
SQ11		For $22.7 \le Q \le 204$ kg; 76 m For $204 < Q < 500$ kg; 381 m	IBD	debris from ECM rear or side
SQ12		For $Q < 22.7$ kg; IBD_{door} For $22.7 \le Q < 500$ kg; IBD_{dmax}	IBD	debris from unbarricaded front of undefined ECM

SQ13		For $22.7 \le Q < 500$ kg; IBD_{dmax}	IBD	debris from barricaded front of any ECM or front of 3 or 7 bar ECM
SQ14		For $Q < 5$ kg; IBD_{dmax} For $5 \le Q \le 223$ kg; 1.5 IBD_{dmax} For $223 < Q < 500$ kg; 450 m	IBD	debris from RC or brick < 20 m^3
SQ15		For $Q < 10$ kg; 61 m For $10 \le Q < 500$ kg; IBD_{dav}	IBD	debris from RC or brick ≥ 20 m^3
SQ16		For $Q < 10$ kg; 61 m For $10 \le Q < 500$ kg; IBD_{dav}	IBD	debris from barricaded light/open structure
	FD8	For $Q \le 400$ kg; 100 m For $400 < Q < 3450$ kg; IBD_{ft} For $3450 \le Q < 4000$ kg; 400 m	IBD	fragments from barricaded light/open structure
	FD10	For $150 \le Q < 4000$ kg; 400 m	IBD	debris from heavy armoured vehicle
SQ17	FD9	For $Q < 45.4$ kg; HFD_1 For $45.4 \le Q < 245$ kg; HFD_2 For $245 \le Q < 500$ kg; 400 m	IBD	fragments from unbarricaded light/open structure

$$IBD_{dav} = -59.132 + 49.105 \cdot \ln(Q) + 1.710 \cdot (\ln(Q))^2$$

$$IBD_{d\,\max} = 64.995 + 7.249 \cdot \ln(Q) + 6.693 \cdot (\ln(Q))^2$$

$$IBD_{door} = 91 + (Q/22.7) \cdot (152 - 91)$$

$$IBD_{ft} = 100 + 5.5 \cdot \sqrt{Q - 400}$$

$$HFD_1 = 107.8 + 24.1 \cdot \ln(Q)$$

$$HFD_2 = -251.9 + 118.6 \cdot \ln(Q)$$

RC or brick structures ≥ 20 m^3: SQ15

[Swisdak et al., 2002] proposed two IBD datafits based on UK trials with brick storehouses [Hoing, 2008]. Figure 15 shows the data together with an “average” and a “maximum” curve fit. In [SQQD WP, 2015] it was decided to use the average curve (SQ15) as IBD for brick and RC magazines with an internal volume larger or equal than 20 m^3. At 500 kg it takes a step upwards to 400 m.

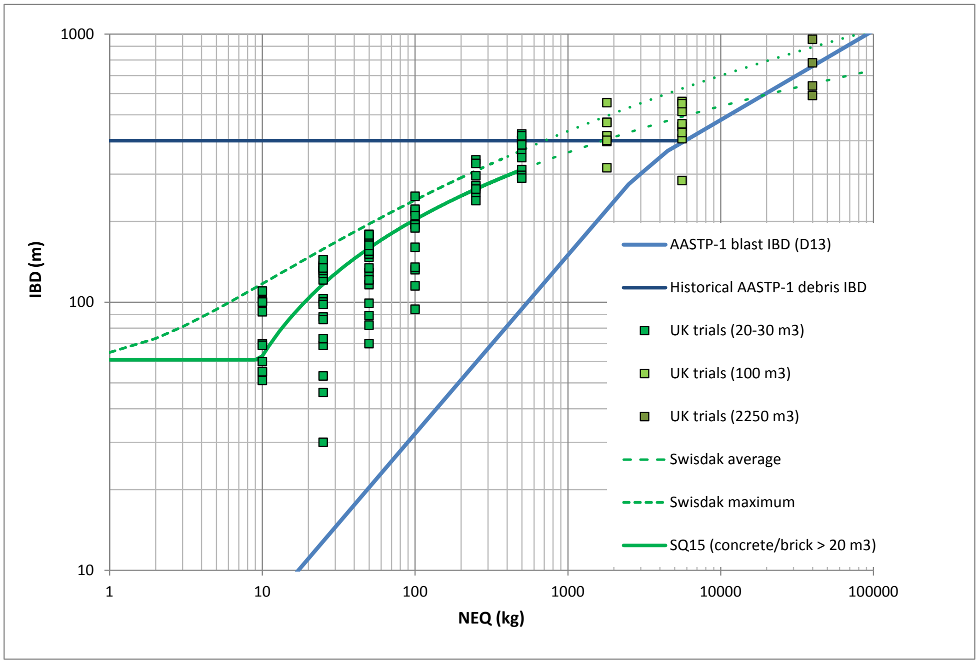


Figure 15. Debris IBD versus NEQ for UK trials together with a datafit by [Swisdak, 2002].

RC or brick structures < 20 m3: SQ14

Trials with 8 m^3 RC Kasun structures [among others Grønsten et al., 2009] yield significantly larger IBDs as is shown in Figure 16.

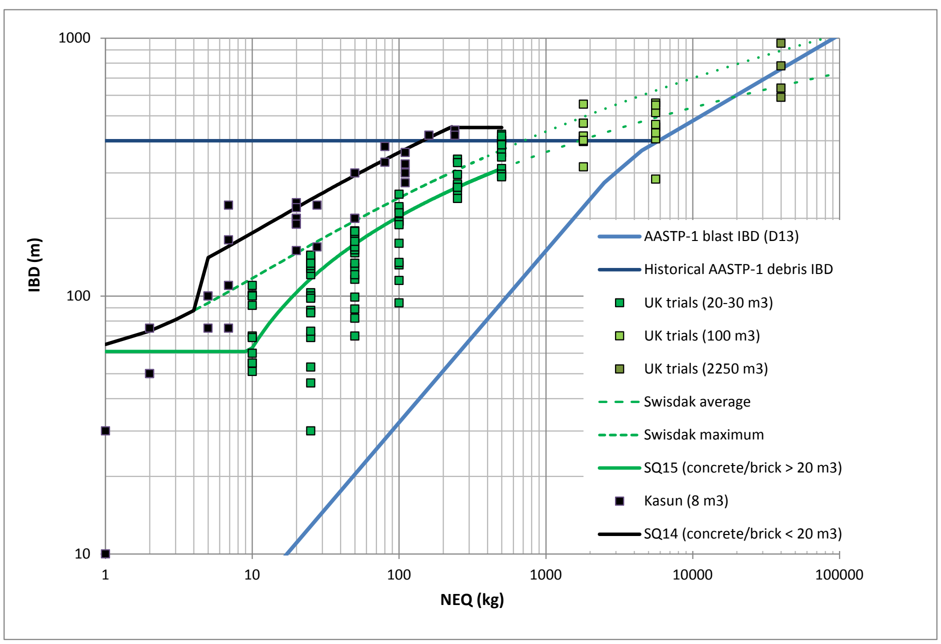


Figure 16. Debris IBD as in Figure 15, with data from Kasun trials added.

The small internal volume causes a relatively high loading density, launch velocity and debris impact distance. SQ14 was defined for RC or brick structures smaller than 20 m^3. The equation used is in fact equal to 1.5 times the maximum curve defined by [Swisdak et al., 2002]. At 500 kg it takes a step downwards from 450 to 400 m.

RC or brick structures, large quantities (Q > 500 kg).
The Sci Pan trials [among others Conway et al., 2015] have shown that for larger quantities of HD1.1 the debris IBD can be much larger than 400 m, and also larger than the original average datafit (Figure 17). Current efforts of AC/326 SGC are aimed to address this aspect.

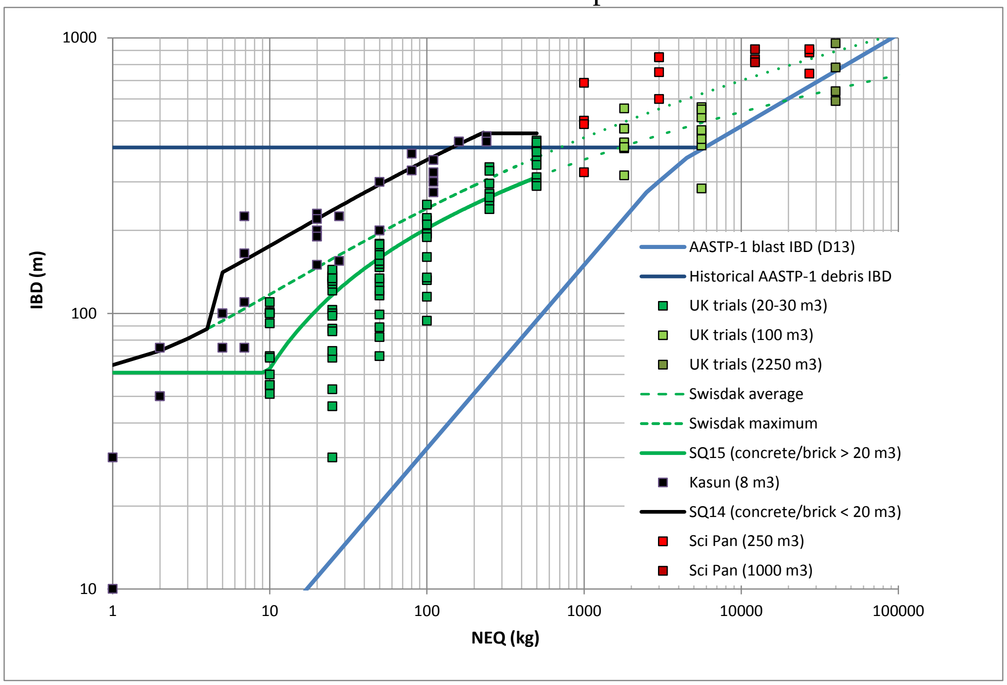


Figure 17. Debris IBD as in Figure 15, with data from Sci Pan trials added.

ECMs: SQ11, SQ12 and SQ13
Not much data is available on small NEQ in ECMs. In the Hastings igloo tests [Reeves et al., 1984] small high explosive charges where detonated in concrete arch magazines with relatively light doors. The magazine headwalls faced an earth-backed concrete blast shield at about 4.5 m. Small charge masses ranging from 5.4 kg to 18 kg, only resulted in the launch of the door and damage or failure to the headwall without any significant debris throw. Charges from 27 kg to 68 kg placed in the center of the igloo resulted in concrete debris being projected over the barricade. The German Dahn Fischbach tests [1997-1998] showed a limited displacement of heavy ECM doors (5 m for 4 kg, 20 m for 8 kg).

Analysis by [Ross et al., 2010] and [van der Voort et al., 2015] resulted in the following QDs:

- SQ11: For the side and rear of any ECM the debris IBD has the fixed values as in Table 6. Below 18 kg (later increased to 22.7 kg) debris is not relevant and the debris IBD was set to zero. A blast IBD is however still relevant in this regime.
- SQ12: For the unbarricaded front of an undefined ECM, due to a lack of data, the debris IBD was set equal to the aforementioned maximum datafit [Swisdak et al., 2002]. Below 22.7 kg the debris IBD was set equal to an estimate for the door throw distance based on calculations with TRAJCAN [Chrostowski, 2014].
- SQ13: For the barricaded front of any ECM or the front of a 3 or 7 bar ECM the debris IBD was again set equal to the maximum datafit [Swisdak et al., 2002]. Below 22.7 kg it was assumed that the door displacement will be limited (either because of the front barricade or because of a heavy door), and that the blast IBD will dominate.

Barricaded light/open structures: debris (SQ16) or fragments (FD8)
Barricaded light or open structures are treated differently in [SQQD WP, 2015] and AASTP-5.

- In the first case (SQ16) it is assumed that debris from a light structure (e.g. an ISO container) constitutes the main hazard. Because of a lack of data for this situation, the conservative choice was made to adopt the earlier mentioned average datafit (=SQ15), although that was based on tests with unbarricaded brick structures.
- In the latter case (FD8) it is assumed that vertically launched primary fragments from the ammunition stack are the main hazard. Fragment pick-up data from the aforementioned 5 tonnes trial (Figure 8) and the 1 tonne Canadian TDM trial [Anderson, 2008] could be well reproduced with fragment throw simulations by [van der Voort et al., 2008]. Figure 18 (left) shows the fragment density (number of hits per m^2) as a function of distance that followed from the 5 tonnes trial and from the simulations. Simulation results for other NEQ are also shown. This leads to IBD predictions shown in Figure 18 (right).

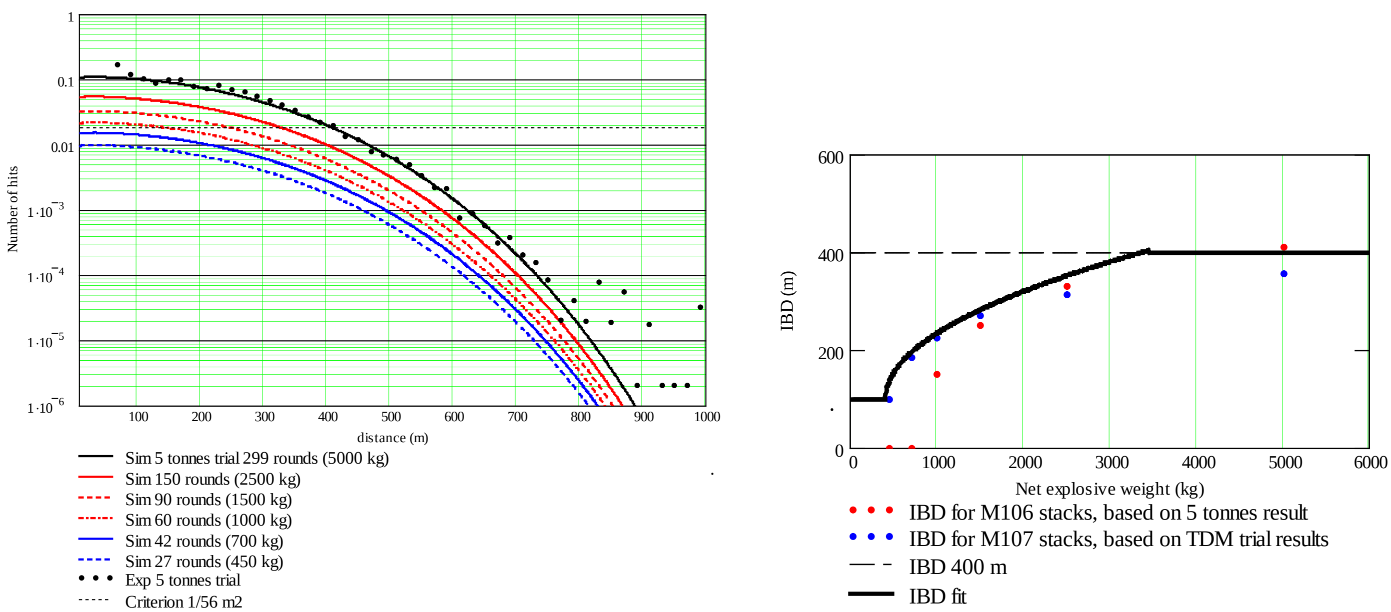


Figure 18. Left: Simulation of 5 tonnes trial together with experimental data. Right: Extrapolation of IBD to other NEQ together with FD8 [Anderson et al., 2008].

Unbarricaded light structures (SQ17 and FD9)
For unbarricaded light structures the primary fragments dominate the hazard. For this case the IBD has been set equal to the US Hazardous Fragment Distance (HFD). This relation is based on trials with single ammunition items. HFDs have been reported for numerous types of ammunition in [DDESB TP16, 2012]. However, a general relation exists as well which returns an HFD based on NEQ only [DOD 6055.09-M, 2012]. The relation has been cut off at 400 m beyond 245 kg. For SsD1.2.3 the HFD has to be determined for a single round.

Heavy armoured vehicle
Experiments have shown that for Q >150 kg a heavy armoured vehicle generates significant debris, which remains below 400 m.

FRAGMENTS FROM HD1.2 EVENTS

Introduction

In this section we will present the QDs that are based on fragmentation in HD1.2 events.

IBD, PTRD, and EWD for SsD1.2.1 and 1.2.2 events

The IBD for SsD1.2.1 and 1.2.2 events are based on the NATO HD1.2 Test Program [Swisdak et al., 1998]. IBDs have been obtained in a similar fashion as described in the previous section, i.e. by means of the PTN method. Although the projection hazard builds up over time, it has been assumed that exposed persons will remain at their initial location and not try to flee to a safe location. An overview of the IBDs that have been obtained from the test data is shown in Figure 19.

Table 7. Overview of HD1.2 fragment QDs.

QD	Equation	Application
D1	$28.127 - 2.364 \cdot \ln(Q) + 1.577 \cdot (\ln(Q))^2$	SsD 1.2.2 IBD
D2	$-167.648 + 70.345 \cdot \ln(Q) - 1.303 \cdot (\ln(Q))^2$	SsD 1.2.1 IBD
D3	$0.36 \cdot D1$	SsD 1.2.2 EWD
D4	$0.36 \cdot D2$	SsD 1.2.1 EWD
D5	$0.67 \cdot D1$	SsD 1.2.2 PTRD
D6	$0.67 \cdot D2$	SsD 1.2.1 PTRD

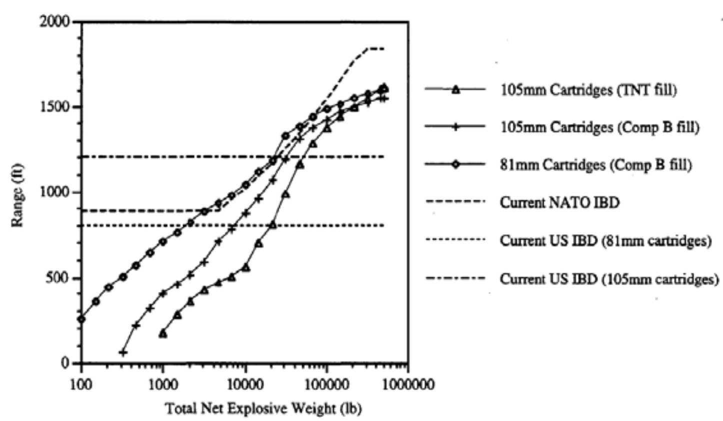


Figure 19. Estimates of the IBD for SsD1.2.1 based on tests with 105 and 81 mm cartridges [Swisdak, 2002] in US units.

In analogy to blast, the PTRD was set equal to 2/3 times IBD, while the EWD was set equal to 0.36 times IBD. Note that the effects of the MCE were already covered in a previous section. The MCE determines the IMDs and also poses minimum distances for the IBD, PTRD, and EWD.

THERMAL EFFECTS

Within the current scope thermal effects are important because they impact the IBD for large quantities of SsD1.2.3 and HD1.6. The relation used has been borrowed from HD1.3: D4 = $6.4 \cdot Q^{1/3}$. For SsD 1.2.3 in barricaded storage the thermal effects are excluded.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents a structured approach to QDs, starting with the amount of munitions involved in the munitions response, and then treating each explosion effect separately. It has been shown that many of the QDs given in the standards are consistent with state-of-the-art prediction models for blast wave propagation and damage. QDs for Small Quantities of explosives (SQQD) are dominated by debris and fragments and have a solid experimental basis in most cases.

A number of aspects have been identified that cause the AASTP-1 to be conservative:

- For HD1.1 all AE in a magazine is assumed to participate in a mass detonation. When the ammunition is spatially separated and in the case of storage of mixed HDs this assumption may be conservative.
- Blast QDs are mostly based on peak overpressure. The dependency on impulse is not consistently addressed, which leads to overestimations.
- Attenuation for blast from the front of an ECM, and from non-earth covered above ground structures in general is neglected.
- Debris QDs are based on the wall-normal direction. The debris hazard in other directions is generally much smaller.
- For SsD1.2.1 the assumed default MCE of 50 kg is an overestimation.
- For SsD1.2.1 and 1.2.2 the projection hazard builds up over time. Nevertheless it has been assumed that exposed persons will remain at their initial location and not try to flee to a safe location.

However, the following aspects may cause potentially unsafe situations:

- At the Explosive Workshop Distance severe damage (level B) is to be expected for brick walled buildings. Collapse of the workshop, lethality and injury are likely to occur.
- For NEQ larger than 500 kg tests have shown that debris IBDs exceed the fixed minimum distance of 400 m. Current efforts of AC/326 SGC are aimed to address this aspect.
- For NEQ and MCE smaller than 50 kg most IMDs have been set to “No QD”. This might not be justified for small RC and brick storage buildings, which may generate high debris velocities. It is advised to assess the resistance of the ES construction against debris impact in such cases.
- Although the door of a PES represents only one or just a few large pieces of “debris”, the size, mass and potential impact distance make it a relevant object to take into account. So far the hazard of launched ammunition magazine doors is only taken into account in the IBD for small quantities of AE. A further assessment of the hazard for large NEQ would be desirable. Specific attention should be given to door- and barricade designs that prevent the launch of a door.

MSIAC promotes further development of the standards to address these issues.

A number of knowledge gaps have been identified as well:

- The background of some IMDs is described in references which are currently unavailable. As a result the rationale for some of the IMDs and their application to certain PES-ES combinations is not available.

- The limited validity of blast models for small scaled distances makes it impossible to verify some of the IMDs for ECMs.
- Debris IBDs for ECMs are based on very few test data. Current test- and modeling efforts conducted by the Klotz Group, and in particular Singapore, may provide useful new input.

MSIAC helps to fill in knowledge gaps by building a repository of all relevant information, and following developments in various expert groups.

The following recommendations have been made with respect to harmonization:

- A large overlap exists between the AASTP-1 QDs, SQQDs and AASTP-5 FDs. Harmonization between the various distances could be considered in order to reduce the number of tables. An example is that AASTP-1 and 5 take different approaches for the IBD of barricaded light structures.
- The addition of SQQDs for small quantities of HD1.1 will be a major improvement. It is recommended to investigate the impact of that work on the QDs for SsD 1.2.1, 1.2.3, and HD1.6.
- AASTP-1 contains QDs for one, two or three protection levels per PES-ES combination. A more consistent approach is recommended. In particular, a QD that offers a high protection level should always be given.

Current efforts of AC/326 SGC are aimed to address these aspects, with MSIAC providing technical support.

With respect to QDs for Insensitive Munitions (IM), SsD1.2.3 and HD1.6, the following recommendations are made:

- The approach taken for SsD1.2.3 and HD1.6 slightly differs, while the rationale for this is not clear. Furthermore, the QD table given for a relatively high unit load of 1,000 kg HD1.6 may lead to confusion. It is recommended to develop a consistent approach for the QDs of IM.
- The thermal effects caused by a stack of IM on fire dominate the IBD for large NEQ. It is however the question if the thermal effects of a stack of IM are currently well represented by QDs that were originally developed for HD1.3 propellants. It is recommended to perform fire tests with large stacks of IM. In addition, QDs for HD1.3 in ECM, and brick and concrete structures do not reflect the potential debris hazards associated with over-pressurization, and those need to be investigated further as well.
- QDs for SsD1.2.3 do not address a thermal hazard when the stack is barricaded. It is recommended to investigate whether a barricade will indeed offer protection for ES against thermal effects for very large NEQ.
- According to AASTP-5 all HDs need to be aggregated as HD1.1, including SsD1.2.3 and 1.6. This means that on deployed missions the benefits of IM in storage situations cannot be exploited. Efforts to address IM in AASTP-5 are recommended.

MSIAC and its member nations have a special interest in IM and promote further development of related QDs.

Recommendations for the long term are:

- A development towards more physics-based QDs in combination with clear acceptance criteria in terms of explosion effects or consequences is recommended. QDs with a larger fidelity avoid the need to split up tables for different NEQ ranges, with associated discontinuity problems at the boundaries. It also avoids the need to make assumption for situations that require “No QD”.

- More advanced debris IBD models could be used that take into account building parameters like dimensions, wall thickness and door properties, and also provide reduced QD in off-normal directions.
- The development of QDs could benefit from a closer cooperation with expert groups on testing and modeling of explosion effects and consequences. Examples are the Klotz Group and the AASTP-4 CWG. Ideally speaking the explosion effect models reported in AASTP-4 and QDs and FDs provided in AASTP-1 and AASTP-5 should be consistent.
- Instead of presenting QDs in table format, they could be provided by means of a calculation tool. This prevents human error, and also avoids issues about rounding and interpolation.

AUTHOR BIOGRAPHY AND ACKNOWLEDGEMENTS

The authors of this paper have been involved in developing, teaching and applying the NATO standards.

Martijn van der Voort has 15 years experience in explosives safety and risk analysis. At MSIAC he is responsible for the topic of ammunition storage and transport safety. He participates in various expert groups, and provides technical support to AC/326 SGC. Before joining MSIAC in October 2015, Martijn worked as a scientist and project manager at TNO in the Netherlands.

Tom Taylor, currently retired, is Martijns predecessor at MSIAC. Prior to MSIAC, Tom was the explosives safety manager for US Army HQ in Europe and has been deployed on multiple occasions. Johan de Roos, currently retired, had a career at the Belgian MoD as an explosives safety officer and instructor. Eric Deschambault, currently retired, but formerly a member of the US Department of Defense Explosives Safety Board (DDESB), was the US AC/326 Delegate from 2008 to December 2016 and was a key leader/participant in the effort to update current NATO HD 1.1 and HD 1.2 criteria and develop new NATO SQQD criteria. Because of Eric's previous in-depth knowledge and involvement, as well as his identification of future work still needed in those areas as detailed in SGC Working Papers, MSIAC contacted Eric regarding the technical content of this paper.

We would like to acknowledge Dr. Matthew Andrews (MSIAC, UK), Ben Keefe (MSIAC, UK), Robert Conway (NF EXWC, US), Stephen Gillström McLean (DOSG, UK), Philip van Dongen (TNO, NLD), Rolf van Wees (TNO, NLD) and Daniel Granados (AFSC, US) for their review and useful input. Valuable feedback was also obtained during presentation of the results at the Klotz Group meeting (12-14 April, 2016), the AC/326 SGC meeting (14-18 March, 2016), and the AASTP-4 CWG meeting (9-13 November, 2015).

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