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Posted Date: 26 July 2023

doi: 10.20944/preprints202307.1741.v1

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Article

# Recommended Separation Distances for 1.3 Ammunition and Explosives

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**Abstract:** Separation Distances are used throughout the world to protect people and assets from the potential hazardous effects from propellants, explosives, and pyrotechnics. The current separation distances for Hazard Division (HD) 1.3 substances and articles used in the United States, in some cases, may not adequately protect against the effects from heat flux and debris when those substances and articles are ignited in a confined structure. Multiple tests in such a confined scenario with HD 1.3 substances have shown that the heat flux and debris hazards could result in injury at distances beyond the current specified explosives safety separation distance (ESSD). Herein are recommended ESSD's for confined as well as unconfined HD 1.3 articles and substances based on the analysis of hundreds of tests. Recommended ESSD's include a smaller value for unconfined quantities less than 100 kilograms and ESSD's that are consistent with NATO distances for confined substances and articles.

**Keywords:** propellant; HD1.3; safe separation; quantity distance

## 1. Introduction

Safe manufacturing and staging of energetic substances and articles requires stand-off distances to reduce the severity of the effects in an ignition scenario. The United States Department of Defense has specified those stand-off distances in the Defense Explosives Safety Regulation 6055.09 (DESR) [1]. Within that document are stand-off guidelines for the different divisions of energetics such as hazard division (HD) 1.3 which are substances and articles that primarily burn or deflagrate. The stand-off distance is known as the Explosives Safety Separation Distance or ESSD. The ESSD to an inhabited building (i.e. Inhabited Building Distance, IBD) is the distance required to protect structures occupied by people both inside and outside Department of Defense property lines. Protection is for blast pressures and effects, debris or fragments, and thermal hazards.

Multiple recent results (see for example References [2–4]) have shown that the current HD 1.3 ESSD in the DESR may not adequately protect against the hazards from burning propellants, explosives, or pyrotechnics when in a structure that does not provide adequate venting (i.e. a confined scenario). Accident scenarios (see Reference [2]) of confined HD 1.3 materials have also shown that in some cases debris hazards can be significant. One such scenario is called out in the DESR 6055.09 in Section V1.E8.4.1.3:

Where there is minimal venting and structural containment (extreme confinement), an [explosion] of the HD 1.3 may occur with effects similar to those of an HD 1.1 explosion. For example, HD 1.3 AE is considered HD 1.1 (mass explosion) for QD purposes when stored in underground chambers.

Despite the above quoted language, the HD 1.3 separation distances for other confined scenarios could be better defined. Herein are recommended explosives safety separation distances for confined HD 1.3 ammunition and explosives (AE). Prior to presenting those ESSD's as a function of net explosive

weight (NEW), the heat flux and debris test data showing recent and legacy results are presented for both confined and unconfined scenarios. Table 1 summarizes the collection of references with test or modeling data compiled for over 100 tests and over 600 data points. The majority of the test data is from open burning of barrels of propellant as described in References [5–7]. Fireworks were also tested in various configurations as reported by TNO in Reference [8].

**Table 1.** HD 1.3 Test and Modeling Measurements with References.

Reference	Propellant Types	# of Tests	# of Measurements	Event Type
Hay J. E. et al. [5]	IMR5010, M1-8-SP, M1-8-MP, WC844, WC846, WCBlank	49	206	Unconfined: Heat Flux
Pape R. et al. [6]	M1, WC844	46	79	Unconfined: Heat Flux
Wyssen [9]	GP11, 35mm powder	17	176	Unconfined: Heat Flux
Paquet F. et al. [10]	SB1, SB2, DB1, DB2	16	48	Unconfined: Heat Flux
Harmanny A. [8]	Fireworks	16	16	Unconfined: Heat Flux
Wyssen [11]	20 mm powder	6	120	Unconfined: Heat Flux
Guymon C. G. [7]	WC814	1	4	Unconfined: Heat Flux
Guymon C. G. [12]	Model	-	30	Unconfined: Heat Flux
Williams M. R. et al. [13]	MTV	12	36	Confined: Heat Flux
Trinkler [14]	Cordite	8	35	Confined: Heat Flux
Blankenhagel P. et al. [15]	di-tert-butyl peroxide	3	9	Confined: Heat Flux
Farmer et al. [3]	M1	3	3	Confined: Heat Flux
Joachim C E [16]	M1	3	3	Confined: Heat Flux
Allain L. [17]	LB 7 T 72	2	12	Confined: Heat Flux
Titan Crane Failure [18]	Rocket Propellant	1	1	Confined: Heat Flux
Wilson et al. [19]	Rocket Propellant	1	1	Confined: Heat Flux
Farmer et al. [3]	M1	2	2	Confined: Debris
Farmer et al. [20]	M1	1	2	Confined: Debris
Wilson et al. [19]	Rocket Propellant	1	1	Confined: Debris
Guymon C. G. [21]	Model	-	25	Confined: Debris

Each test scenario consists of a collection of propellant with a given mass. That mass is then ignited and the resulting heat flux is measured at one or more distances away from the event to quantify the amount of thermal radiation. The heat flux values together with burn times are used to calculate the safe distance and are summarized graphically in the sections that follow.

The explosives safety separation distance (ESSD) and how it relates to the heat flux magnitude and duration is defined in the next section. After that, the calculated ESSD for unconfined HD 1.3 scenarios are compared with the IBD in the current DESR 6055.09. Then, the deficiency in the current ESSD for confined HD 1.3 scenarios will be shown concluding with the recommended distances for protection against those confined HD 1.3 events.

## 2. Explosives Safety Separation Distance Definition

An explosives safety separation distance from a substance, article, or structure with reacting material, specifically burning material, is one where an individual would not receive second degree burns and would not be exposed to hazardous debris (<79 Joules) at a density greater than one fragment per six-hundred square feet. These standards are from the Defense Explosive Safety Regulation (DESR) 6055.09 as outlined in Sections V1.E8.2.2.4 and V1.E8.2.2.5 [1].

Thus, determining the safe distance from a HD 1.3 event requires quantifying the heat flux and debris hazards. The debris generated from an event can be quantified and the distance at which the fragment count per 600 square feet decreases below 1 can be found. The heat flux allowed decreases with increasing exposure time per the equation in Section V1.E9.3.1.2 of the DESR 6055 where the allowable exposure time is per Equation 1:

$$t = 200 \cdot q^{-1.46} \quad (1)$$

In all the analysis reported on here, the maximum exposure time was assumed to be 20 seconds which corresponds to a heat flux of 4.84 kW/m<sup>2</sup> or 0.116 cal/(cm<sup>2</sup>· sec). If the burn time was longer than 20 seconds, that 4.84 (or 0.116) value was the allowable heat flux. The 20 second exposure time maximum is a conservative estimate of the duration of time an individual would need to move away from the event. The allowable heat flux is one which prevents second degree burns. The distance at the allowable heat flux is the explosives safety separation distance (ESSD) for thermal hazards.

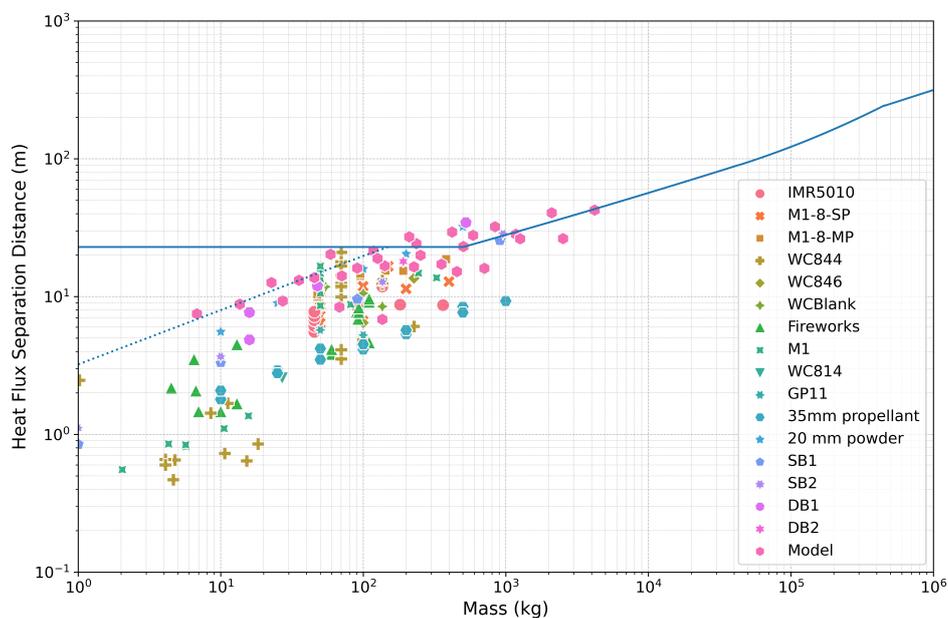
The radiative heat flux received from a high temperature substance decreases with increasing distance. The rate of decrease can depend on the receptor's view factor of the emitting source and the atmospheric conditions between the receptor and the source. Conservatively, that rate of decrease is proportional to the inverse square of the distance and is commonly referred to as the point source model where  $q = \alpha/d^2$ . That point source model can be used to first determine the  $\alpha$  value from experimental or model data and then used to obtain the distance at which the allowable heat flux from Equation 1 could be expected. Enumerated, the methodology used here to obtain the ESSD with each set of test data of burning bulk explosive material is as follows:

1. Obtain the max allowable heat flux from the burn time of the test and Equation 1,
2. Estimate the  $\alpha$  factor in the point source model given the average heat flux data (assumed constant over the duration) at various distances by taking the 75<sup>th</sup> inclusive percentile of the  $q \cdot d^2$  values (the 75<sup>th</sup> percentile is used to better approximate the area of the curve where the allowable heat flux is expected),
3. Using the point source model with the estimated  $\alpha$  factor and a view factor of 1, determine the ESSD that corresponds to the max allowable heat flux.

For example, 47.6 pounds of propellant was burned in the open with an average heat flux of 0.733, 0.467, 0.464, 0.212, and 0.166 cal/cm<sup>2</sup>/sec recorded at distances of 3.2, 4.0, 5.0, 6.4 and 8.0 m, respectively (Reference [5]). The burn time in this scenario was 15 seconds. Per equation 1, the allowable heat flux is 0.141 cal/cm<sup>2</sup>/sec. The  $\alpha$  value is 10.6E4 cal/sec and the safe distance estimated to be 8.7 m.

### 3. Comparison of ESSD to IBD for Unconfined Scenarios

Table 1 lists literature values of more than 100 open burn tests with HD 1.3 substances and a total of over 600 heat flux measurements. From those data, ESSD's have been estimated per the above method. Those distances for each mass were then compared with the current HD 1.3 IBD separation distances. As can be seen in Figure 1, the current separation distances (blue line) for HD 1.3 substances in the DESR 6055.09 protects against second degree burns when those substances are unconfined as almost all of the points are under that blue line. In the cases where ESSD's are above the IBD distance, the test data is likely overly conservative as the burn times from those events were not reported in the literature and so were estimated (see References [10,22] and the csv file at the github site). Also, for some of the literature values, the peak heat flux is reported but the average heat flux for the duration of the burn was not reported. In those cases the average was assumed to be half the peak value.



**Figure 1.** Plot of the unconfined explosives safety separation distances from testing and modeling as reported in References [5–8,12]. The solid blue line is the current HD 1.3 IBD per DESR 6055.09. Almost all of the estimated ESSD distances from the test data are within the current IBD indicating sufficient protection against potential injury for unconfined burning of energetic material. The dotted blue line is the proposed adjustment for smaller masses (<145 kg).

The data from the model shown in Figure 1 is from COMSOL modeling (Ref. [12]) of radiative heat transfer from a source with different diameters and flow rates with a gas temperature of 2800K. Other parameters used in that COMSOL model were fit to single- and multi-barrel data in References [5,7]. That model was then used to predict the ESSD for various other propellant masses and barrel configurations that were not tested. Some of the data from the model is slightly above the IBD line for scenarios with high burn rates. Those points are slightly above the line as the gas temperature is likely too high in the model (2800 K); more realistic temperatures are in the range of 1000 - 2100 K (see for example the fireball temperatures from MTV flares of 1700-1800 K as reported in Reference [23]).

The above results and comparison were for unconfined scenarios (open burning). Confined events of HD 1.3 substances and articles can have much more violent results as presented in the next sections.

#### 4. Unconfined versus Confined Burning

Unconfined burning allows the generated gases to freely exit the immediate area around the substance or article such that the pressure surrounding the substance or article is not elevated significantly. Confined burning is when the gases generated are not able to freely escape due to insufficient venting resulting in an elevated pressure with the exit gaseous flow nearly or fully choked. However, determining if a possible burning scenario results in choked or nearly choked flow requires knowledge of the gas generation rate of the burning HD 1.3 material as well as the potential size and behavior of the gaseous escape routes (vents). Fast running models such as the Integrated Violence Model can be used to obtain an estimate of the internal pressure during the burning event and subsequent violence (Reference [21]). A heuristic to delineate between confined and unconfined scenarios has not yet been developed.

## 5. ESSD for HD 1.3 Confined Scenarios

Confined scenarios where rapidly produced hot gases are not allowed to sufficiently escape can result in a pressurization and violent bursting of the structure. Typically, that violence can scale with the product of the failure pressure and the internal gaseous volume, as is true for pressurized cylinders. Those pressure bursts can generate fragments or debris that can travel long distances in addition to generating a large fireball.

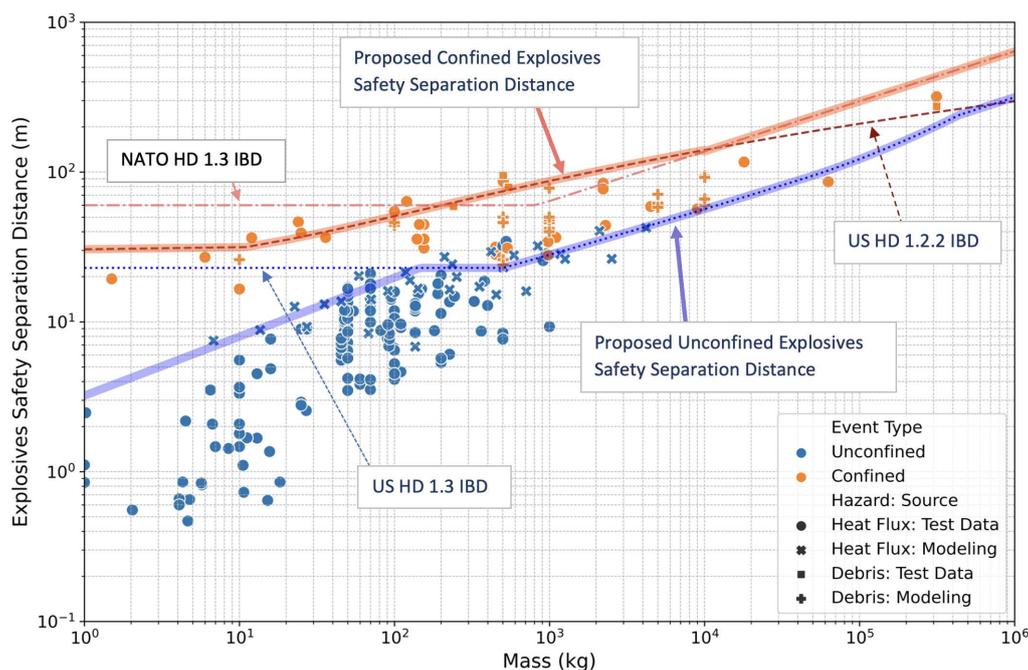
Literature values for multiple confined scenarios are also summarized here, including where the gases are generated more quickly than they are allowed to escape. The confinement where the venting is limited is in concrete structures (References [3,20]), earth covered structures (References [17]), and a very large rocket motor (Reference [18,19]). Some of the test data for the confined scenarios did not have measured heat flux values, but the fireball size was reported or estimated from video. The explosives safety separation distance was then found per the above enumerated steps assuming an average heat flux of  $80 \text{ kW/m}^2$  at the fireball distance. The value of  $80 \text{ kW/m}^2$  is reported by Dorofeev at the surface of a fireball (Ref. [24]). That value is considered conservative as the predicted distance for the allowed heat flux is so far away from the fireball edge. The accuracy of the point source model is relied upon with a power law dependence on distance of 2. In reality it is likely to be greater than 2 due to the atmospheric absorbance of the radiated energy. For example, 2.09 is used in some NATO combustion models [25].

The debris estimates for the confined scenarios are primarily from the Kasun structure testing reported in References [3,20]. A significant amount of work was completed to catalog and mark all of the debris from multiple tests. The Hazardous Fragment Distance (HFD) of 1 hazardous fragment in 600 square feet was then determined. For the Titan rocket motor event, the HFD was estimated as 0.6 times the maximum fragment distance. Integrated Violence Modeling was completed for multiple scenarios where the fragment distances and densities were predicted from the test parameters given the concrete structure fragment size distribution (Ref. [21]).

**Table 2.** Proposed Explosives Safety Separation Distances.

Condition	Mass, M (kg)	Relation (m)
Unconfined	$M \leq 453$	$\min(3.216 \cdot M^{0.3939}, 22.9)$
	$453 < M \leq 43,540$	$\max(22.9, \exp[1.4715 + 0.2429 \cdot \ln(M) + 0.00384 \cdot (\ln(M))^2])$
	$43,540 < M \leq 453,590$	$\exp[5.5938 - 0.5344 \cdot \ln(M) + 0.04046 \cdot (\ln(M))^2]$
	$453,590 < M$	$3.17 \cdot M^{1/3}$
Confined	$M \leq 10,000$	$\max(30.5, 28.127 - 2.364 \cdot \ln(M) + 1.577 \cdot (\ln(M))^2)$
	$10,000 < M$	$6.4 \cdot M^{1/3}$

The majority of both the test and modeling results for the confined scenarios are below the proposed confined explosives safety separation distance as shown in Figure 2. The same is true for the unconfined scenarios. We conclude that the proposed explosives safety separation distances would adequately protect people from the hazards of burning and deflagrating HD 1.3 substances and articles. The relations for the recommended separation distances in Figure 2 are given in Table 2.



**Figure 2.** Plot of the data (as points) for the unconfined (blue) and confined (orange) scenarios. The unconfined data points are repeated from Figure 1. Also shown are the proposed ESSD's (as lines). The recommended unconfined ESSD's (blue line) is per Table 2. The recommended ESSD's for confined scenarios (orange line) above 10,000 kg is the NATO HD 1.3 IBD line, and below 10,000 kg, it is the US HD 1.2.2 IBD.

## 6. Conclusions and Discussion

We have recommended updated ESSD values for HD1.3 substances and articles based on a large amount of test data that would allow for more material at current separation distances when the unconfined quantity is less than 100kg and which better protect people and property for confined scenarios and are consistent with the NATO distances used around the world. The difference between the confined and unconfined cases are currently subjective in that a required vent area limiting the internal gas pressure in the building or structure is not defined. Further work to quantitatively define the difference between the two is needed.

The recommended ESSD's use the average heat flux for the burn duration. Other methods could be used to estimate the separation distance such as using the peak heat flux and a burn duration that also conserves energy which could give slightly higher explosives safety separation distances. The average over the entire burn duration was chosen here due to the layers of conservatism: inverse squared law relating the radiation to distance (more likely a faster decline) and the heat flux and exposure time to prevent second degree burns in Eq. 1 is also conservative.

The recommended ESSD's are not directional. In other words, for the test scenarios that were directional, the ESSD's are reported at the direction where the largest heat flux would be experienced. Directional effects could be accounted for in a straight forward way, for example by including the location information of vents through which the hot gases exit and afterburn. Similarly, instead of using the net explosive weight (NEW) as the key parameter, the ESSD could be related to a different set of key parameters such as the burn rate, loading density, vent area, vent area location, among others. The net explosive weight was used here as the current US and NATO ESSD's are functions of the NEW.

**Author Contributions:** "Conceptualization, C.G., M.L. and J.C.; methodology, C.G.; formal analysis, C.G.; data curation, C.G.; writing—original draft preparation, C.G.; writing—review and editing, C.G. and J.C; All authors have read and agreed to the published version of the manuscript."

**Funding:** "This research received no external funding"

**Data Availability Statement:** The compilation of data together with the reference and summary notes are available in a public github repository ([github.com/clint-bg/publicationdata/safeSeparation](https://github.com/clint-bg/publicationdata/safeSeparation)).

**Acknowledgments:** We acknowledge helpful discussions with Martijn van der Voort and Matt Ferran with the Munitions Safety Information Analysis Center (MSIAC) and for providing some of the referenced heat flux data points.

**Conflicts of Interest:** “The authors declare no conflict of interest.”.

## Abbreviations

The following abbreviations are used in this manuscript:

$m$	mass of energetic substance, kilograms
$d$	distance from substance, article, or structure, meters
$t$	time, seconds
$q$	heat flux, kilowatts per square meter
$\alpha$	point source model parameter, kilowatts

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