Munitions Safety Information Analysis Center

Supporting Member Nations in the Enhancement of their Munitions Life Cycle Safety

FRAGMENTATION FROM DETONATIONS AND LESS VIOLENT MUNITION RESPONSES (MSIAC REPORT O-208)

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Introduction

- An increasing number of munitions now show less violent responses than detonation in cook off or impact scenarios

- Limited quantitative information about physical effects and consequences
- Topic of MSIAC Improved Explosives and Munitions Risk Management (IEMRM) workshop and various MSIAC reports
  - M. Van der Voort, E. Baker and C. Collet, “Physical Effects and Consequences from Detonations and Less Violent Munition Responses,” NATO MSIAC Report L-223, Brussels, Belgium, 2018.
  - C. Collet, E. Baker and M. van der Voort, “History of Natural Fragmentation Models,” NATO MSIAC Report L-234, Brussels, Belgium, 2018.
  - E. Baker, M. Von Ramin and M. van der Voort, “Improved Explosives and Munitions Risk Management Workshop - Focus Area 2B: Fragmentation,” NATO MSIAC Report L-234, Brussels, Belgium, 2019.

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- Fragmentation state of the art
  - Detonative regime
  - Sub-detonative regime
- Trajectory analysis
- Risk-based approach and case study
  - Individual risk
  - Group Risk
- Conclusions

Fragmentation state of the art

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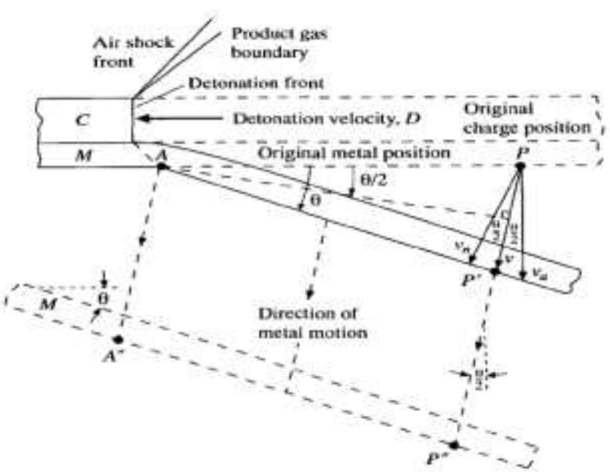
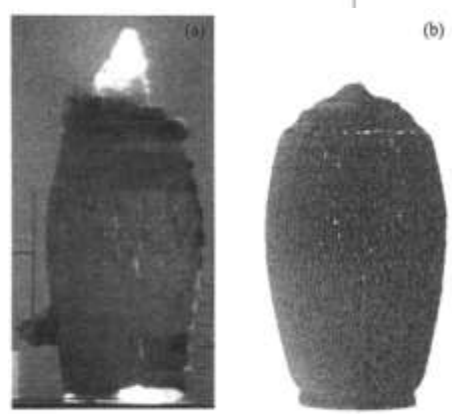
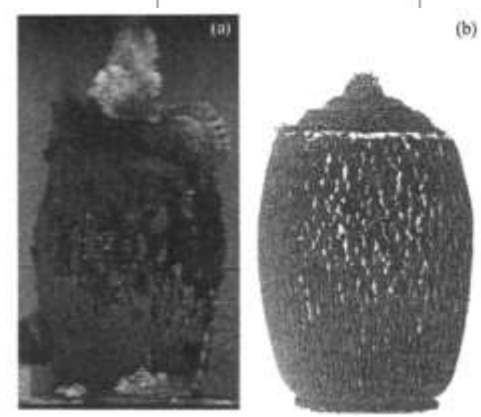
- Mass distribution
  - Mott, Generalized Grady, Held
- Metal casing velocity
  - Gurney, refinements for small L/D
- Metal projection angle
  - Taylor
- Stack effects
  - US TP16

Configuration			Final metal velocity equation	
Symmetric	Sandwich		$V_{max} = \frac{\sqrt{2E}}{\sqrt{\frac{M}{C} + \frac{1}{3}}}$	Equation 2
Symmetric	Infinite length cylindrical case		$V_{max} = \frac{\sqrt{2E}}{\sqrt{\frac{M}{C} + \frac{1}{2}}}$	Equation 3
Symmetric	Spherical case		$V_{max} = \frac{\sqrt{2E}}{\sqrt{\frac{M}{C} + \frac{3}{5}}}$	Equation 4
Symmetric	Finite length cylinder case (Natural fragmentation warhead)		$V_{max} = \frac{\sqrt{2E}}{\sqrt{(\frac{M}{C} + \frac{1}{2})(1 + \frac{(R_0 - T)}{L})}}$	Equation 5[3]
Asymmetric	Sandwich		$V_{M\,max} = \frac{\sqrt{2E}}{\sqrt{\frac{1+A^3}{3(1+A)} + \frac{N}{C}A^2 + \frac{M}{C}}}$ $V_{N\,max} = A.V_{M\,Max}$	Equation 6
Asymmetric	Open face sandwich		$V_{max} = \frac{\sqrt{2E}}{\sqrt{\frac{(1+2\frac{M}{C})^3+1}{6(1+\frac{M}{C})} + \frac{M}{C}}}$	Equation 7







Fragmentation state of the art

- Fragmentation process depends on:
  - Explosive reaction rate
  - Warhead burst volume
  - Fragment explosive contact surface area

- Detonative regime
  - Fragmentation starts after expansion to two times original volume
  - Lasts until three times the original volume

- Sub-detonative regime
  - Lower reaction rate
  - Case wall breaks before reaction completed
  - Lower velocity, fewer number of cracks, fewer but larger fragments
  - Plate- or strip-like shape, thinning of fragments due to case expansion

Fragmentation state of the art

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Experimental data:

- M107 155 mm Comp B artillery shells [Baker, 2009]
  - Non-standard initiation by shaped charge, sub-detonative response
  - Large fragments travelled further due to a lower air drag

840 g steel fragment reaching 1824 m

- Black powder filled ordnance [Crull, 2004]
  - Comparison with Mott and Gurney:
    - Over prediction of number of fragments and velocity
    - Under prediction of fragment sizes and impact distances

Fragmentation state of the art

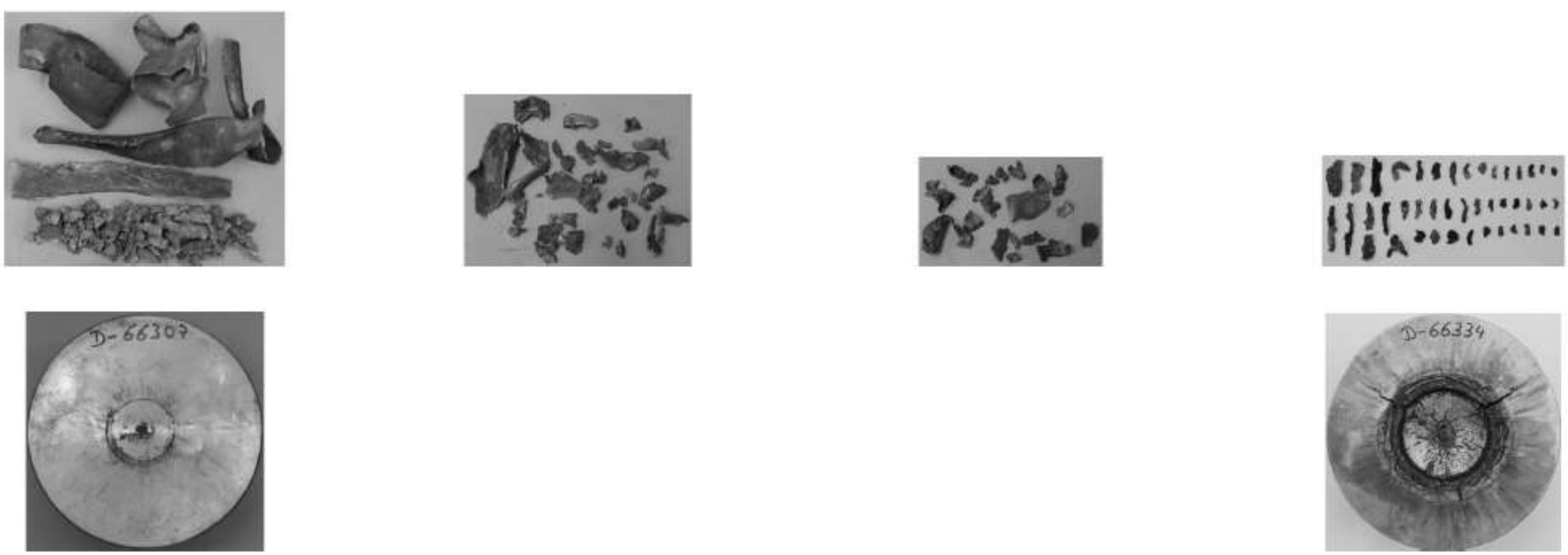
Experimental data:

- Tests with deflagrating munitions [Kinsey, 1992] and [Chick, 1992]
  - Quantification of the large strip-like fragments
  - Fragment velocities are much slower (between 10 and 33% of same detonated munition)
- Tests with tritonal Mk82 bombs [Vercruyssen, 2014]
  - Inspection of 6 MK82 bombs
  - Formation yellow crystals (TNT) in 3 cases
  - These shells give partial detonation and large strip-like fragments

Fragmentation state of the art

Dial a yield technology [Arnold, 2011]

- Selection of a desired munitions response between deflagration and detonation (different initiation strengths)
- A proof of concept was developed and experiments showed that blast and fragmentation effects could be tuned between low and high output.



(a) Low yield: 0 holes–ERL IV

(b) $\Delta t = 80\mu s$: 9 holes–ERL III

(c) $\Delta t = 40\mu s$: 37 holes–ERL II

(d) Full yield: 57 holes–ERL I

Fragmentation state of the art

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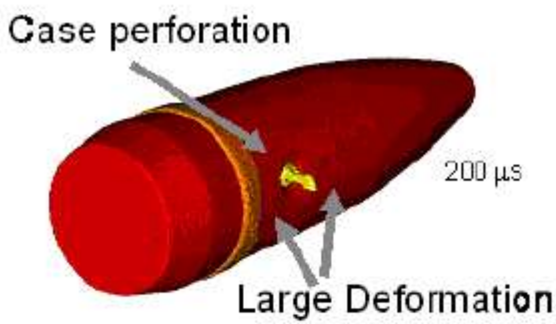
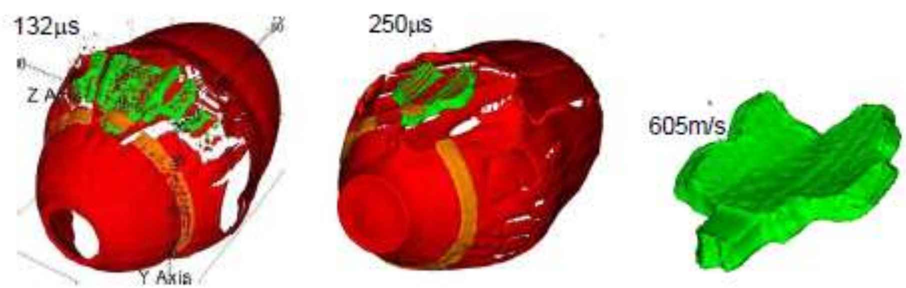
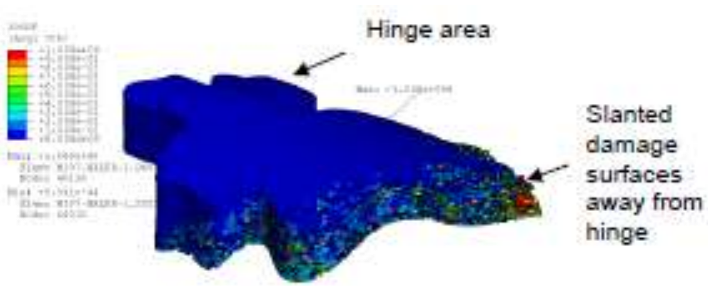
Modelling of **fragment characteristics** for sub-detonative response

- Three dimensional high rate continuum modeling [Baker, 2009]





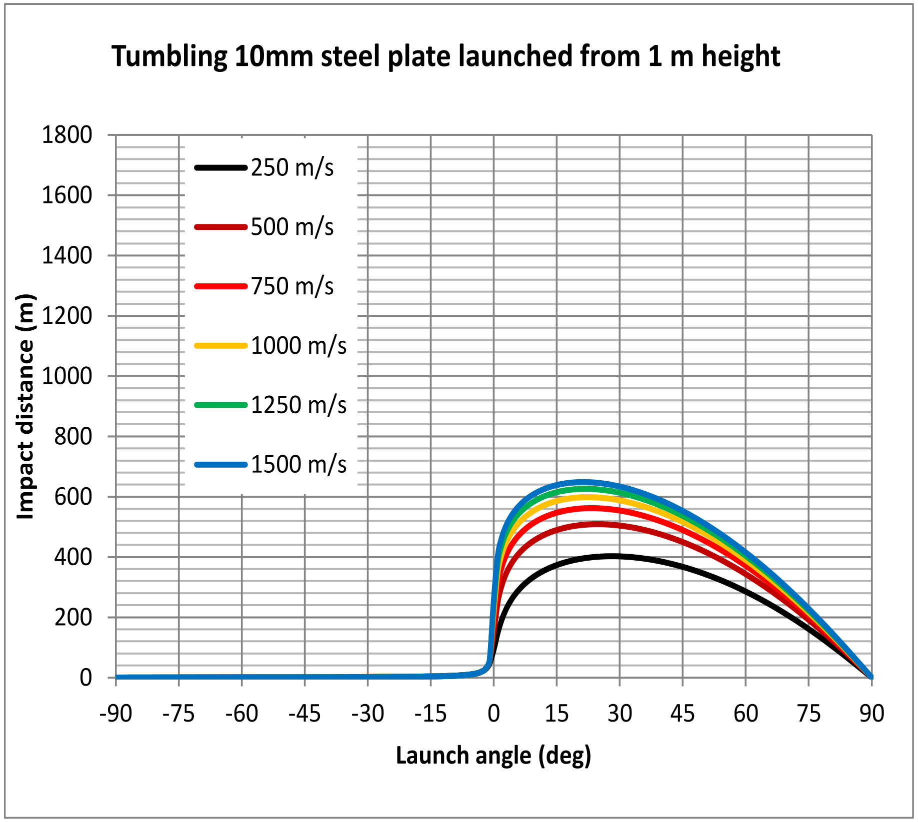
- Successful reproduction of fragment size and shape
- Distance of 1824 m possible due to spin stabilized **edge-on** orientation
- Caused by “hinge”

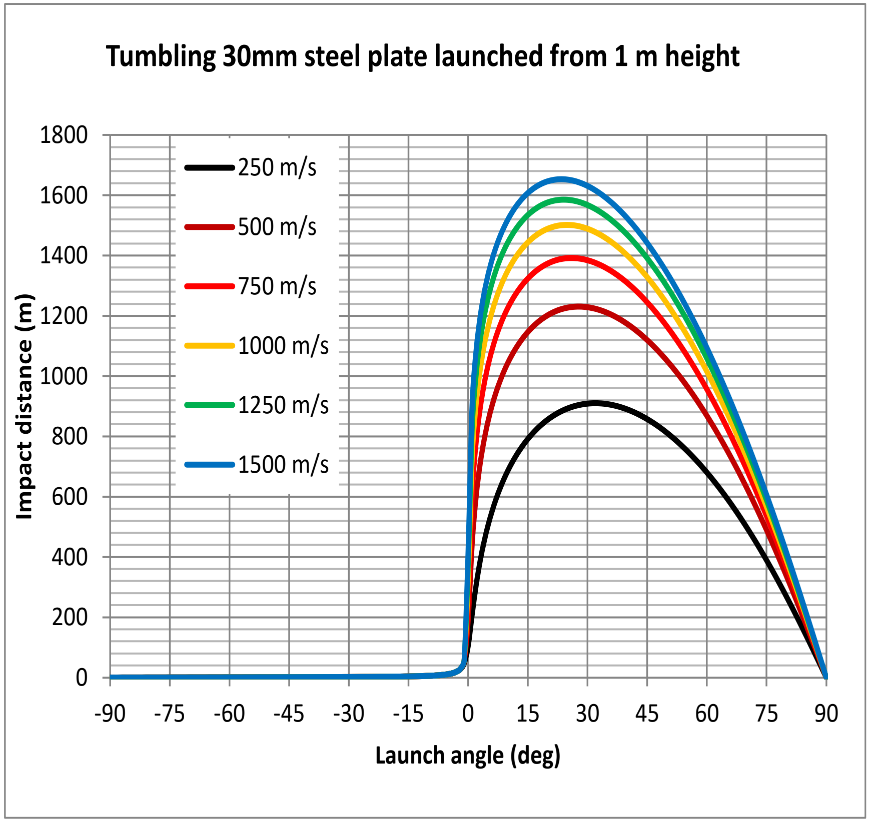


Trajectory analysis

Trajectory analysis with TRAJCAN*

- Fragments modelled as **tumbling** rectangular steel plates
- Strong dependency on plate thickness





**TRAJCAN was developed by ACTA [Chrostowski, 2014]*

Risk-based approach

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- Commonly used "safety" distances:
  - Maximum Fragment Distance (MFD) for intentional detonations
  - Hazardous Fragment Distance (HFD) for accidental detonations

M107 155 mm	Detonation	Deflagration (Baker, 2009)
HFD	137 m	A few m
MFD	801 m	1824 m

- Are MFD and HFD still suitable for deflagrations?

- Alternative metrics: Individual Risk (IR) and Group Risk (GR)

Risk-based approach

- US risk acceptance criteria (AASTP-4)

	Risk to:	DDESB Criteria	Service Guidance
IR related	Any 1 related (a) person (Annual Pf)	Risks below 1 x10^{-4} are acceptable	
GR related	All related (a) people (Annual Ef)	Risks below 1 x10^{-3} are acceptable	If risks are above 1 x10^{-3} apply ALARP principle (c) Accept above 1 x10^{-2} with significant national need only (c)
IR unrelated	Any 1 unrelated (b) person (Annual Pf)	Risks below 1 x10^{-6} are acceptable	
GR unrelated	All unrelated (b) (Annual Ef)	Risks below 1 x10^{-5} are acceptable	If risks are above 1 x10^{-5} apply ALARP principle (c) Accept above 1x10^{-3} with significant national need only (c)

Probability of fatality

- For illustration we consider two case studies

Parameter	Symbol	Case 1	Case 2
		Detonating warhead	Deflagrating warhead
Number of fragments (-)	N	5,000	20
Maximum Fragment Distance (m)	MFD	1,000	2,000
100% lethal distance (m)	RL	21	1.3
1% lethal distance (m)	HFD	211	13

- Probability of fatality
  - Hemispherical expansion of a fragment cloud
  - All fragments equal and assumed lethal
  - Fragment trajectories are straight lines

$$P_f(r) = \begin{cases} 1 \; if \; r \leq R_L \\ \dfrac{N \cdot S}{2 \cdot \pi \cdot r^2} \; if \; R_L < r \leq MFD \end{cases}$$

Probability of fatality

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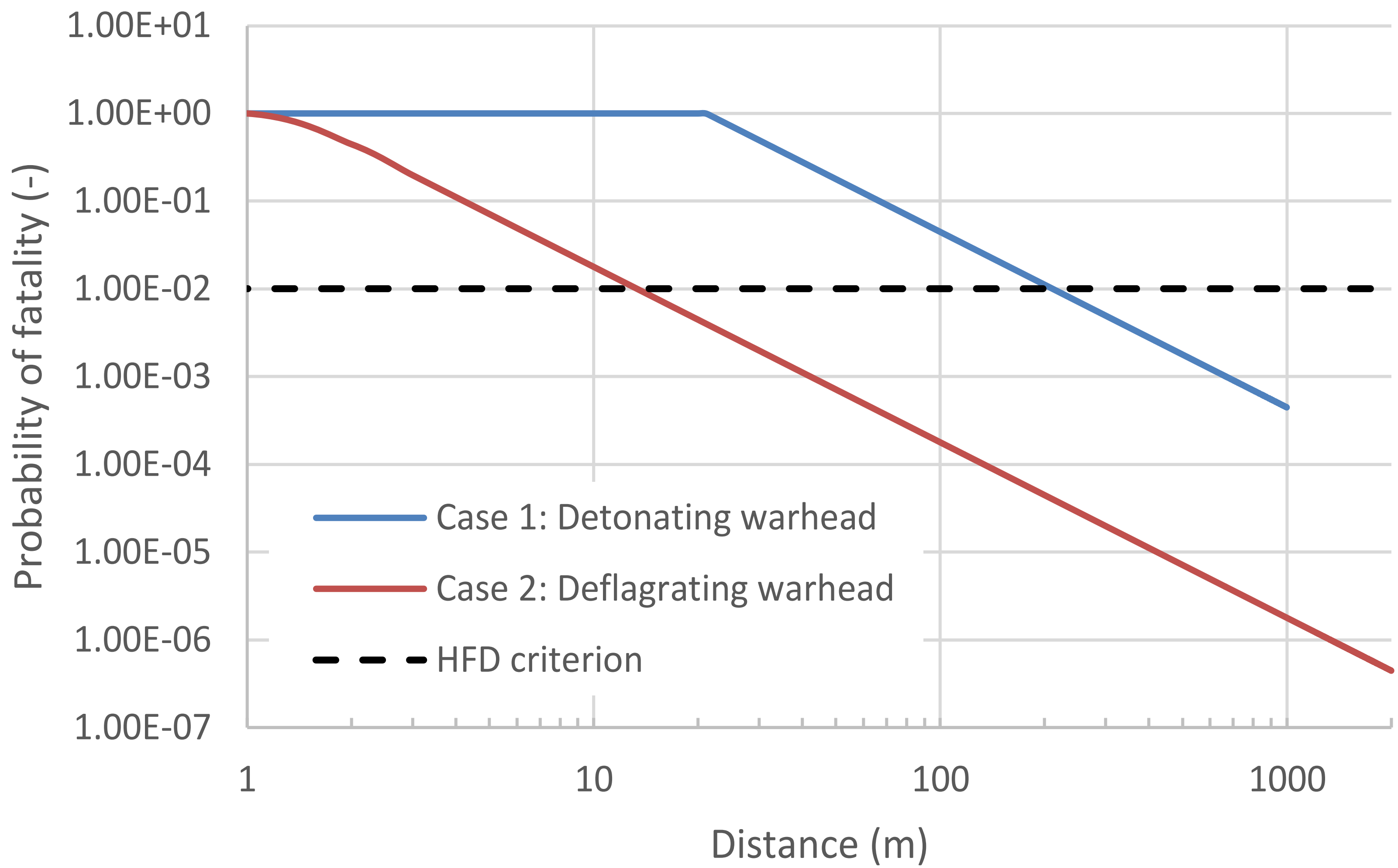

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Annual probability

- US Annual probability of event (AASTP-4)

P(e) Tables: DDESB TP-14 Rev 4
(affected by Compatibility Group)

PES used primarily for:	Probability of Event (PES-year)		
	I	II	III
Burning Ground / Demilitarization / Demolition / Disposal	2.4E-02	2.4E-03	8.1E-04
Assembly / Disassembly / LAP / Maintenance / Renovation	4.7E-03	4.7E-04	1.6E-04
Lab / Test / Training	4.3E-03	4.3E-04	1.4E-04
Manufacturing	1.7E-03	1.7E-03	1.7E-03
Inspection / Painting / Packing	8.2E-04	8.2E-05	2.7E-05
Loading / Unloading	5.7E-04	5.7E-05	1.9E-05
In-Transit Storage (hrs – few days)	3.0E-04	1.0E-04	3.3E-05
Temporary Storage (1 day - 1 mth)	1.0E-04	3.3E-05	1.1E-05
Deep Storage (1 month - year)	2.5E-05	2.5E-05	2.5E-06

Elements	Compatibility Group
I	L, A, B, G, H, J, F
II	C
III	D, E, N

Notes: The elements in the matrix comprise Compatibility Groups. Definitions of the Compatibility Groups can be found in DoD 6055.09-M.

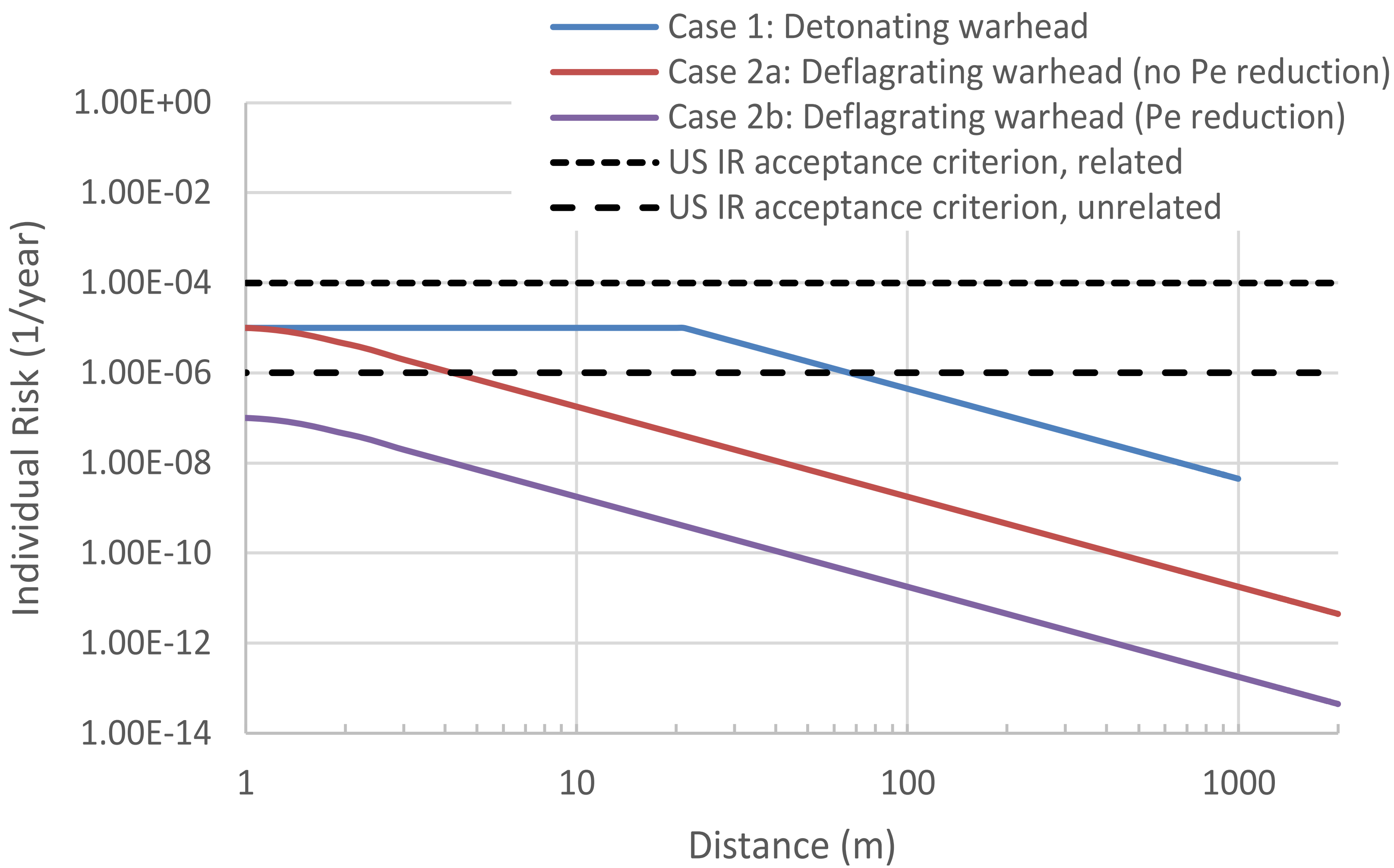
P(e) Tables: DDESB TP-14 Rev 5
(function of Hazard Division)

Activity	HD 1.1/ 1.2/1.5	HD 1.3	HD1.6
Assembly / Disassembly / LAP / Maintenance / Renovation	5.37E-04	1.61E-03	5.37E-06
Burning Ground / Demil / Demolition / Disposal		7.78E-03	
Lab / Test		9.75E-04	
Training	9.75E-04	2.92E-03	9.75E-06
Loading / Unloading	3.15E-05	9.45E-05	3.15E-07
Inspection / Painting / Packing	2.05E-04	6.16E-04	2.05E-06
Manufacturing		1.90E-03	
Storage	1.20E-05	3.59E-05	1.20E-07

- Assumed for this case study:
  - Case 1 (detonating warhead): Pe = 1E-5/year
  - Case 2 (deflagrating warhead) two options:
    - A. Pe = 1E-5 / year (no probability reduction)
    - B. Pe = 1E-7 / year (probability reduction)

Individual Risk

$$IR(r) = P_e \cdot P_f(r)$$



Individual Risk

- Comparison with criteria

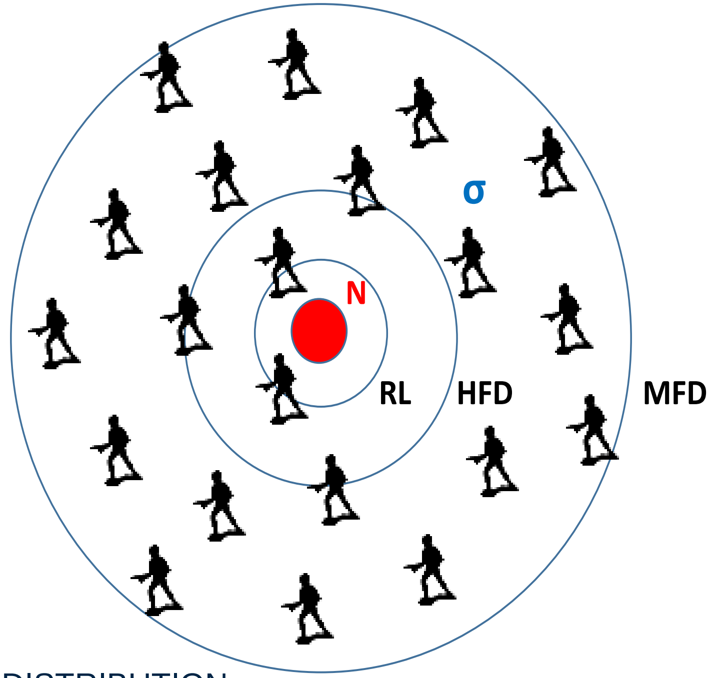
Parameter	Symbol	Case 1	Case 2a	Case 2b
		Detonating warhead	Deflagrating warhead	Deflagrating warhead
			No Pe reduction	Pe reduction
Probability of event (1/year)	Pe	1E-5	1E-5	1E-7
Distance to IR criterion for related persons (m)	$R_{IR10\text{-}4}$	Criterion always met	Criterion always met	Criterion always met
Distance to IR criterion for Unrelated persons (m)	$R_{IR10\text{-}6}$	66	4.2	Criterion always met

Group Risk

- Expected number of fatalities
- For uniform populations density σ (1/m2)

$$N_f = \int_0^{MFD} P_f(r) \cdot 2 \cdot \pi \cdot r \cdot \sigma \cdot dr = \int_0^{R_L} 2 \cdot \pi \cdot r \cdot \sigma \cdot dr + \int_{R_L}^{MFD} \frac{N \cdot S}{2 \cdot \pi \cdot r^2} \cdot 2 \cdot \pi \cdot r \cdot \sigma \cdot dr$$

$$N_f = N \cdot S \cdot \sigma \cdot \left[\frac{1}{2} + ln \left(MFD \cdot \sqrt{\frac{2 \cdot \pi}{N \cdot S}} \right) \right]$$



Group Risk

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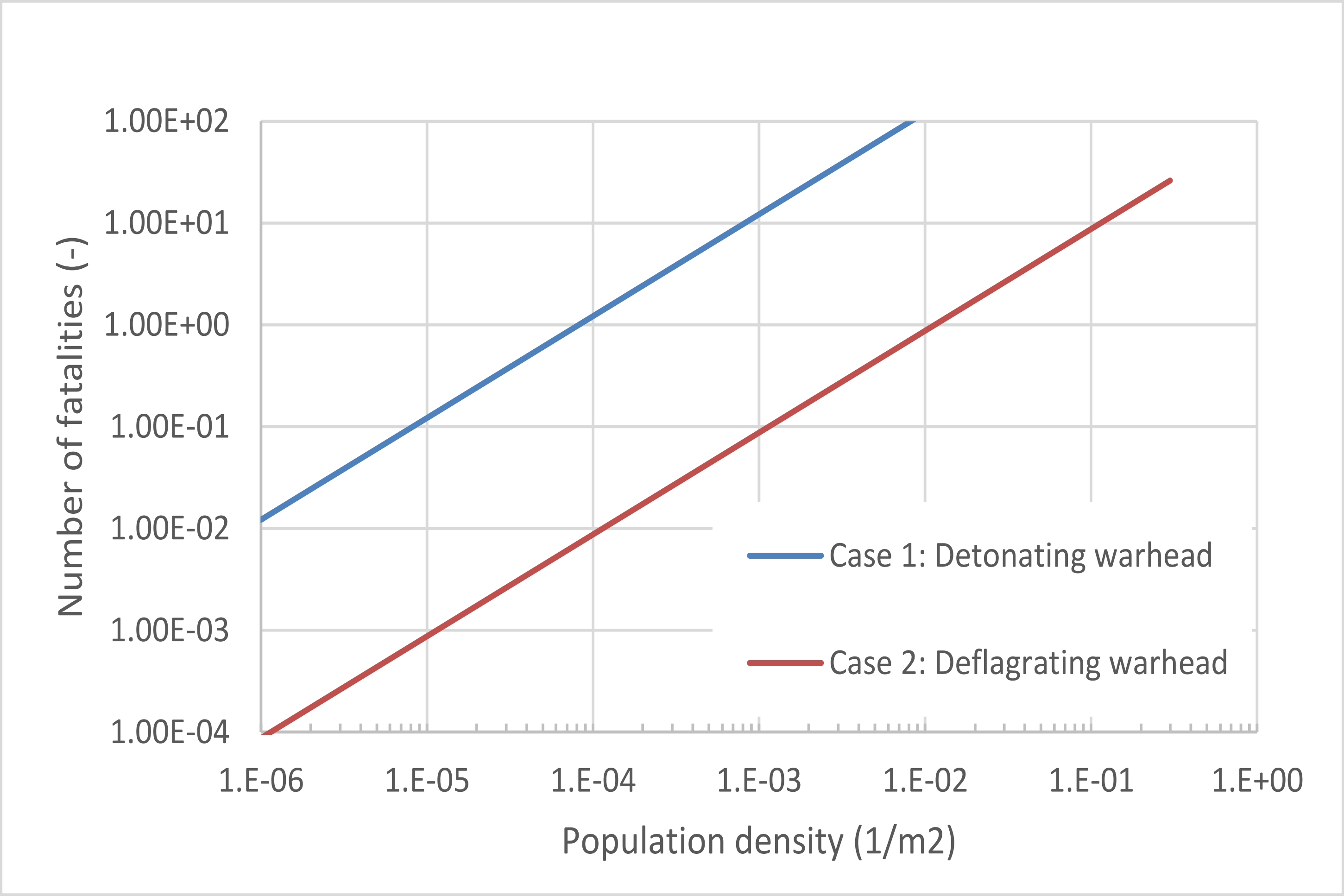
- Expected number of fatalities versus populations density



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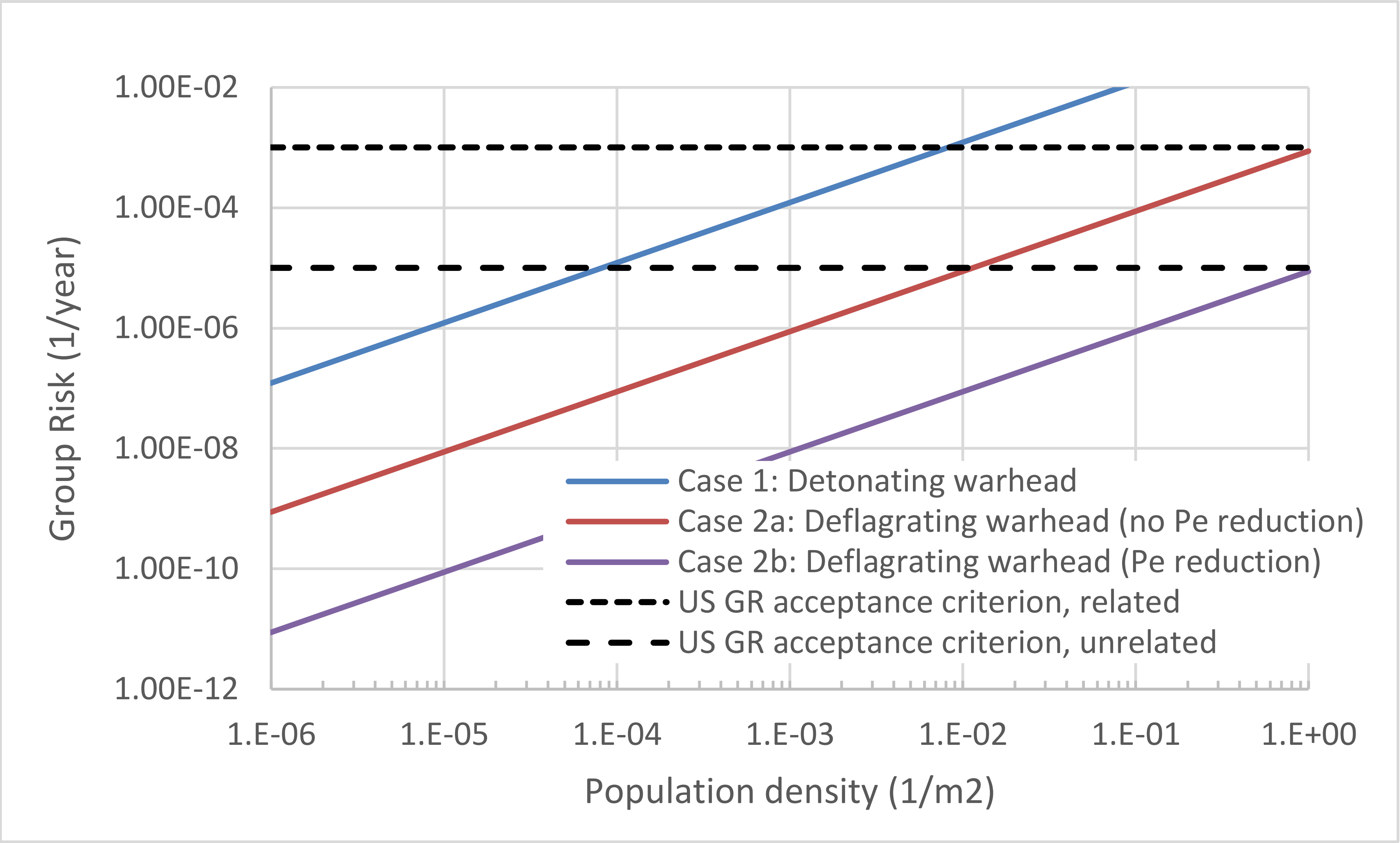
Group Risk



Group Risk

Parameter	Symbol	Case 1	Case 2a	Case 2b
		Detonating warhead	Deflagrating warhead	Deflagrating warhead
			No Pe reduction	Pe reduction
Probability of event (1/year)	Pe	1.00E-5	1.00E-5	1.00E-7
Population density satisfying GR criterion for related persons ($1/m^2$)	$\sigma_{GR10\text{-}3}$	1E-2 (1 every 10 by 10 m)	1 (1 every 1 by 1m)	Criterion always met*
Population density satisfying GR criterion for unrelated persons ($1/m^2$)	$\sigma_{GR10\text{-}5}$	1E-4 (1 every 100 by 100 m)	1E-2 (1 every 10 by 10 m)	1 (1 every 1 by 1m)

Conclusions

- Fragmentation modeling has evolved significantly with increasingly realistic predictions, even for less violent explosions and deflagrations
- Individual Risk and Group Risk criteria have been explored as an alternative to the MFD and HFD
- Brings more nuance and takes into account:
  - Lower probability of initiation
  - Nature of the ammunition activities
  - Population density
  - Related (personnel) or unrelated (third party)
- Can help answer questions in which environment/ under which conditions munitions can be handled.
- Further development possible with more advanced fragmentation models