

#### **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 0-208)



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### Introduction

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



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- 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.





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



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







#### 

- 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



### 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



### 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







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)  $\triangle t = 80 \mu s$ : 9 holes-ERL III

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

(d) Full yield: 57 holes–ERL I



### Fragmentation state of the art

# 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 with TRAJCAN\*

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



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



# **Risk-based approach**

- 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	ALL DESCRIPTION
MFD	801 m	1824 m	mission of or considering the

- 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)

IR relatedRisk to:DDESB CriteriaService GuidanceIR relatedAny 1 related (a) person (Annual Pf)Risks below 1 x10-4 are acceptableIf risks are above 1 x10-3 apply ALARP principle (c) Accept above 1 x10-2 with significant national need only (c)GR relatedAny 1 unrelated (b) person (Annual Pf)Risks below 1 x10-6 are acceptableIf risks are above 1 x10-3 apply ALARP principle (c) Accept above 1 x10-2 with significant national need only (c)IR unrelatedAny 1 unrelated (b) (Annual Pf)Risks below 1 x10-6 are acceptableIf risks are above 1 x10-5 are acceptableSR unrelatedAll unrelated (b) (Annual Ef)Risks below 1 x10-5 are acceptableIf risks are above 1 x10-5 apply ALARP principle (c) Accept above 1 x10-3 with significant national need only (c)					
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	GR unrelated			Accept above 1x10 <sup>-3</sup> with significant national need only (c)	
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# **Probability of fatality**

For illustration we consider two case studies

Deveneter	Cumhal	Case 1	Case 2	
Parameter	Symbol	Detonating warhead	Deflagrating warhead	
Number of fragments (-)	Ν	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

$$1 \text{ if } r \leq R_L$$

$$P_f(r) = \frac{N \cdot S}{2 \cdot \pi \cdot r^2} \text{ if } R_L < r \leq MFD$$



## **Probability of fatality**

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# **Annual probability**

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#### US Annual probability of event (AASTP-4)

#### P(e) Tables: DDESB TP-14 Rev 4

(affected by Compatibility Group)

Deep Storage

(1 month - year)

PES used	Probability of Event (PES-year)				Elements	Compatibility Group	Activity	HD 1.1/ 1.2/1.5	HD 1.3	HD1.
primarily for:	1	Ш	III (		1	L, A, B, G, H, J, F	Assembly/Disassembly/			
Burning Ground /	2 45 02	0.45.00	0.45.04	Ν	1	C	LAP / Maintenance / Renovation	5.37E-04	1.61E-03	5.37E-0
Demolition / Disposal	2.4E-02	2.4E-03	6.1E-04		III Notes: The	elements in the	Burning Ground / Demil /		7.78E-03	
Assembly/		4.7E-04	1.6E-04		matrix com	prise Compatibility	Demolition / Disposal			
Disassembly/LAP/ Maintenance/ Renovation	4.7E-03				Groups. Definitions of the Compatibility Groups can be found in DoD 6055.09-M.		Lab/Test		9.75E-04	
				Ц			Training	9.75E-04	2.92E-03	9.75E-0
Lab/Test/Training	4.3E-03	4.3E-04	1.4E-04	Ľ			Loading/Unloading	3.15E-05	9.45E-05	3.15E-0
Manufacturing	1.7E-03	1.7E-03	1.7E-03				Inspection / Painting / Packing	2.05E-04	6.16E-04	2.05E-0
Inspection / Painting / Packing	8.2E-04	8.2E-05	2.7E-05				Manufacturing		1.90E-03	
Loading/Unloading	5.7E-04	5.7E-05	1.9E-05				Storage	1.20E-05	3.59E-05	1.20E-0
In-Transit Storage (hrs – few days)	3.0E-04	1.0E-04	3.3E-05							
Temporary Storage (1 day - 1 <u>mth</u> )	1.0E-04	3.3E-05	1.1E-05							

#### P(e) Tables: DDESB TP-14 Rev 5

(function of Hazard Division)

#### Assumed for this case study:

2.5E-05 2.5E-05 2.5E-06

- 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

		Case 1	Case 2a	Case 2b	
Parameter	Symbol	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 <sub>IR10-4</sub>	Criterion always met	Criterion always met	Criterion always met	
Distance to IR criterion for Unrelated persons (m)	R <sub>IR10-6</sub>	66	4.2	Criterion always met	



# **Group Risk**

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

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

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



### Expected number of fatalities versus populations density

**Group Risk** 



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### **Group Risk**

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# **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 <sup>2</sup> )	σ <sub>gr10-3</sub>	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 <sup>2</sup> )	σ <sub>gr10-5</sub>	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