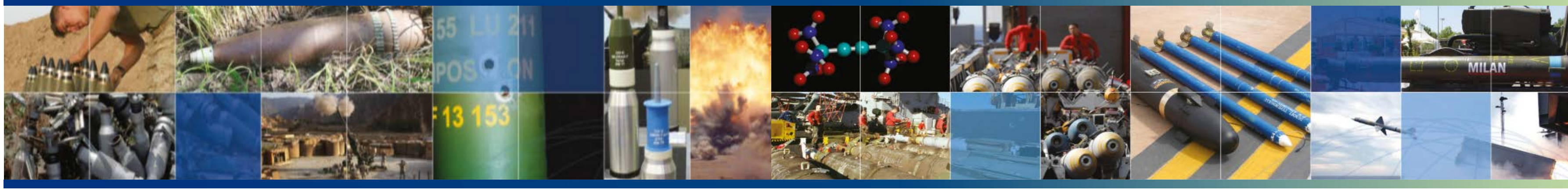
Munitions Safety Information Analysis Center

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



PHYSICAL EFFECTS AND CONSEQUENCES FROM DETONATIONS AND LESS VIOLENT MUNITION RESPONSES

IESS, San Diego, 6-9 August 2018

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Improved Explosives and Munitions Risk Management
Granada, Spain | 10 - 14 September 2018

MSIAC UNCLASSIFIED

Introduction

- Munitions with a less violent response than Detonation (type I) in cook off or impact scenarios

	Munitions Response
I	Detonation
II	Partial Detonation
III	Explosion
IV	Deflagration
V	Burn
VI	No Reaction

- For Deflagration (type IV) and Explosion (type III) reactions, limited quantitative information about physical effects and consequences

- Improvements in the risk management of such munitions, quantification of the safety benefits (QDs / risk)

Response descriptors in AOP-39 Ed. 3

- Qualitative description, more quantitative data needed!

Response Level	Energetic Materials (EM)	Case	Blast	Fragment or EM projection	Other
Type I (detonation)	Prompt consumption of all EM once the reaction starts	(P) Rapid plastic deformation of the metal casing contacting the EM with extensive high shear rate fragmentation	(P) Shock wave with magnitude & timescale = to a calculated value or measured value from a calibration test	Perforation, fragmentation and/or plastic deformation of witness plates	Ground craters of a size corresponding to the amount of EM in the munition
Type II (partial detonation)		(P) Rapid plastic deformation of some, but not all, of the metal casing contacting the EM with extensive high shear rate fragmentation	(P) Shock wave with magnitude & timescale < than that of a calculated value or measured value from a calibration test Damage to neighbouring structures	Perforation, plastic deformation and/or fragmentation of adjacent metal plates. Scattered burned or unburned EM.	Ground craters of a size corresponding to the amount of EM that detonated.
Type III (explosion)	(P) Rapid combustion of some or all of the EM once the munition reaction starts	(P) Extensive fracture of metal casings with no evidence of high shear rate fragmentation resulting in larger and fewer fragments than observed from purposely detonated calibration tests	Observation or measurement of a pressure wave throughout the test arena with peak magnitude << than and significantly longer duration that of a measured value from a calibration test	Witness plate damage. Significant long distance scattering of burning or unburned EM.	Ground craters.
Type IV (deflagration)	(P) Combustion of some or all of the EM	(P) Rupture of casings resulting in a few large pieces that might include enclosures or attachments.	Some evidence of pressure in the test arena which may vary in time or space.	(P) At least one piece (casing, enclosure or attachment) travels beyond 15m with an energy level > 20J based on the distance/mass relationship used for HC[1]. Significant scattered burning or unburned EM, generally beyond 15 m.	(P) There is no primary evidence of a more severe reaction and there is evidence of thrust capable of propelling the munition beyond 15m. Longer reaction time than would be expected in a Type III reaction.
Type V (burn)	(P) Low pressure burn of some or all of the EM	(P) The casing may rupture resulting in a few large pieces that might include enclosures or attachments.	Some evidence of insignificant pressure in the test arena.	(P) No item (casing, enclosure, attachment or EM) travels beyond 15m with an energy level > 20J based on the distance/mass relationship used for HC[1]. (P) A small amount of burning or unburned EM relative to the total amount in the munition may be scattered, generally within 15m but no further than 30m.	(P) No evidence of thrust capable of propelling the munition beyond 15m. For a rocket motor a significantly longer reaction time than if initiated in its design mode.
Type VI (no reaction)	(P) No reaction of the EM without a continued external stimulus. (P) Recovery of all or most of the unreacted EM with no indication of a sustained combustion.	(P) No fragmentation of the casing or packaging greater than that from a comparable inert test item.	None	None	None

Introduction

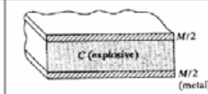
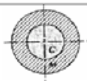
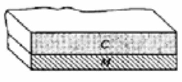
- Physical effects
  - **Primary fragmentation**
  - Internal blast and debris
  - **External blast (or pressure) waves**
  - Thermal effects

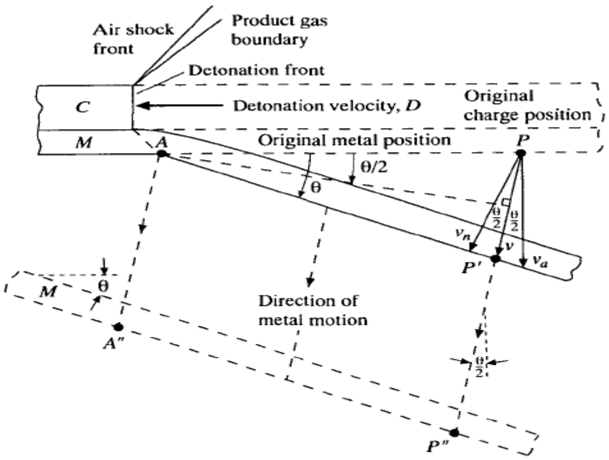
- In storage conditions, the larger scale and confinement introduces additional complexities.

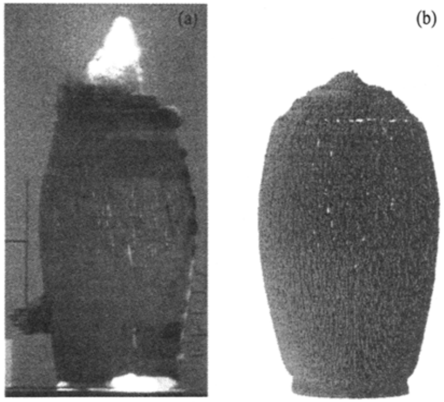
- This presentation discusses relevant data and presents a first step towards the development of models

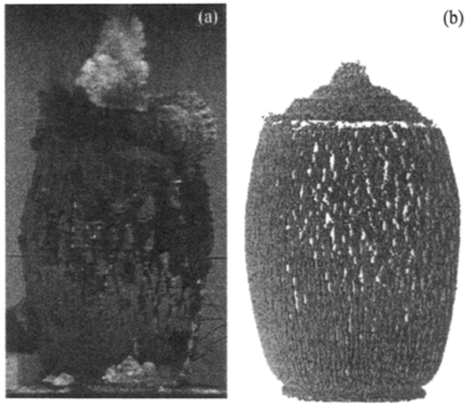
Primary fragmentation

- Fragmentation state of the art (detonation):
  - 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







Primary fragmentation

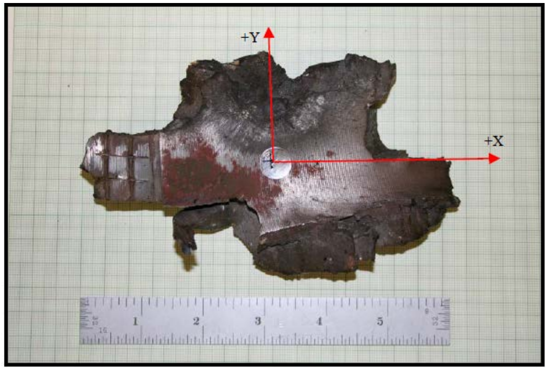
- Fragmentation process depends on:
  - Explosive reaction rate
  - Warhead burst volume
  - Fragment explosive contact surface area
- Detonative regime
  - Fragmentation starts after expansion to two times original volume
  - Lasts until three times the original volume
- Sub-detonative regime
  - Lower 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

Primary fragmentation

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

Primary fragmentation

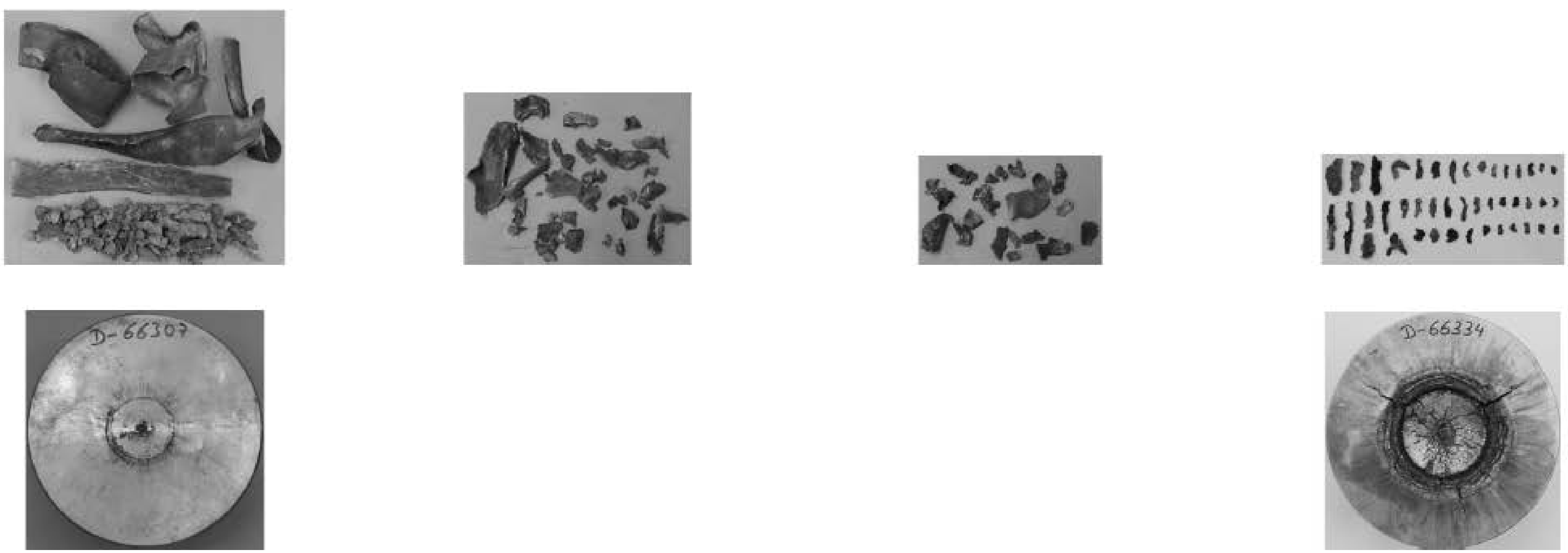
Experimental data:

- 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

Primary fragmentation

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

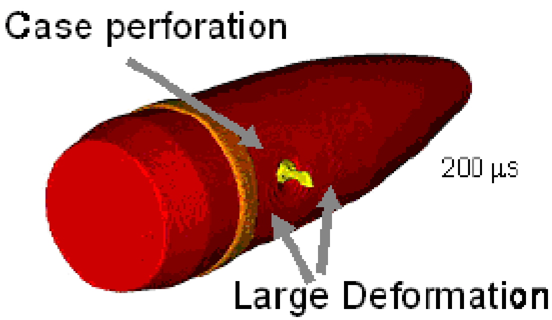
(c) $\Delta t = 40\mu s$: 37 holes–ERL II

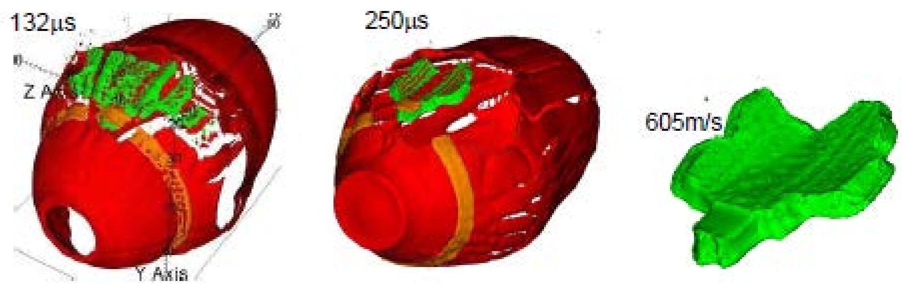
(d) Full yield: 57 holes–ERL I

Primary fragmentation

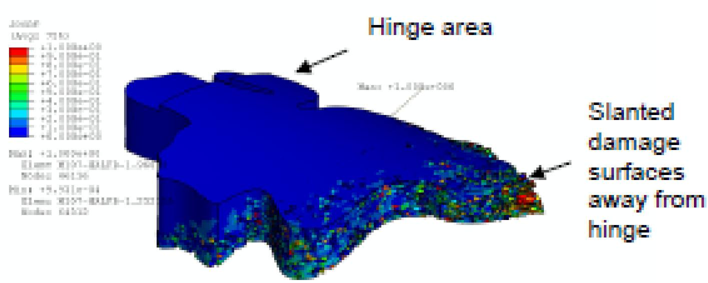
Modelling of **fragment characteristics** for sub-detonative response

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





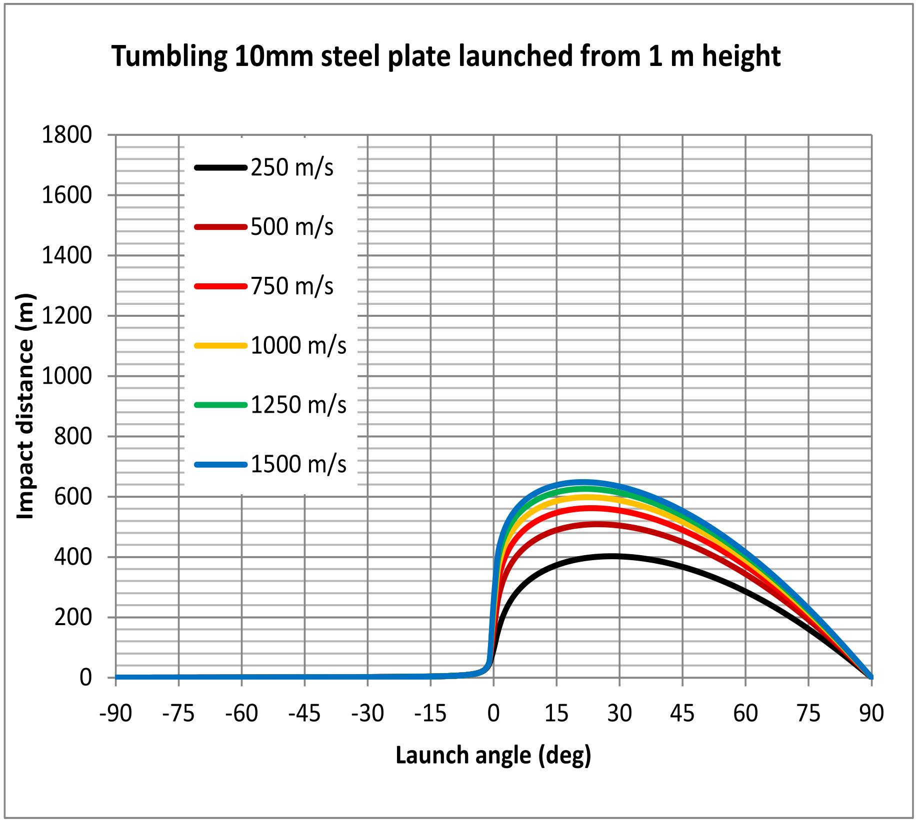
- Successful reproduction of fragment size and shape
- Distance of 1824 m possible due to spin stabilized **edge-on** orientation
- Caused by “hinge”

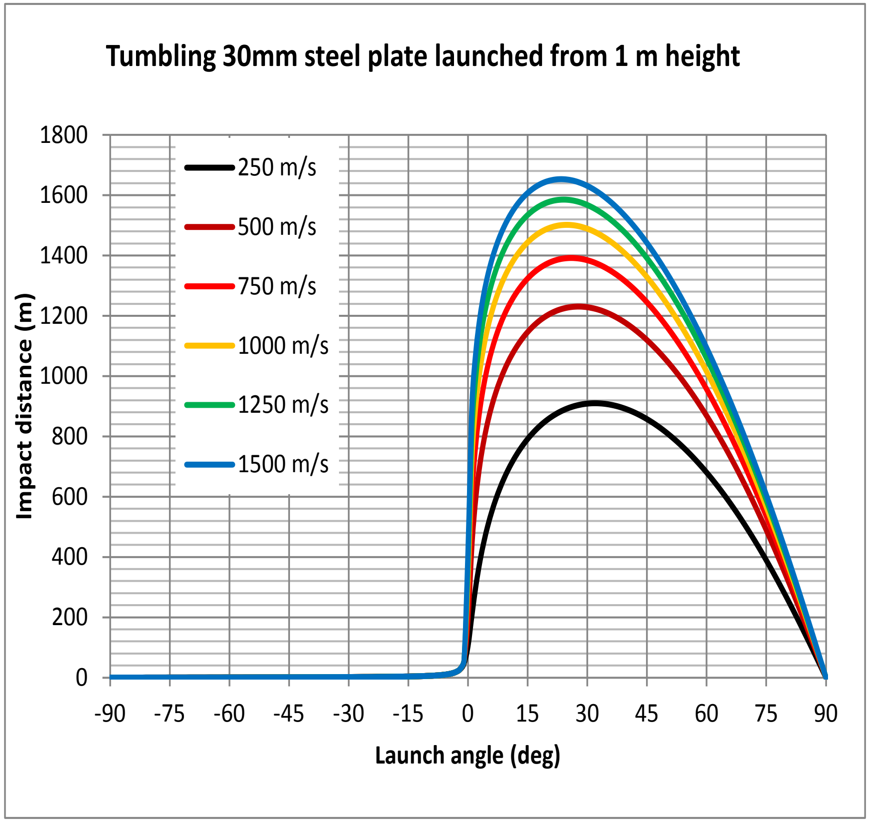


Primary fragmentation

Trajectory analysis with TRAJCAN*

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





*TRAJCAN was developed by ACTA [Chrostowski, 2014]

Primary fragmentation

A few large fragments that reach large distances!

- Maximum Fragment Distance (MFD) is very large
- Hit probability and Hazardous Fragment Distance (HFD) may be very small

What is an appropriate methodology to determine safety distances?

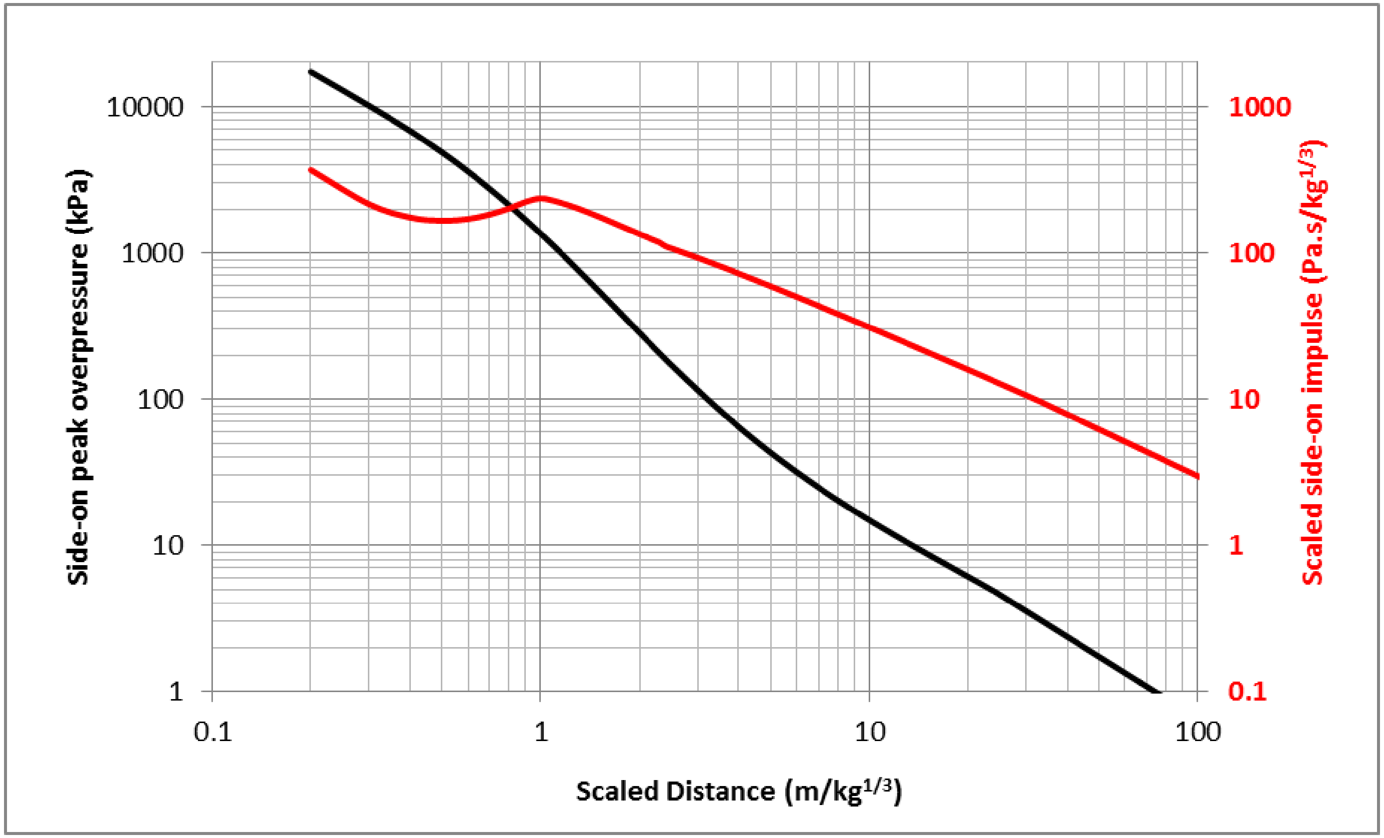
- MFD, HFD or another approach?

Conclusions (fragments)

- Reduced reaction rate leads to:
  - Larger strip-like fragments
  - Smaller velocity
- Modelling of **fragment characteristics**
  - Possible with 3D high rate continuum modelling
  - Engineering models are still missing
- Modelling of **fragment trajectories**
  - Possible with correct assumption about orientation
  - "Edge-on" or "Tumbling"
- Safety Distances
  - What is an appropriate definition, MFD, HFD, other?

External blast

- Engineering models for blast parameters
  - Blast Effects Computer [TP20, June 2018] & [AASTP-4, 2016]
  - Reference case is hemispherical surface burst



$$Z = \frac{R}{Q^{1/3}}$$

External blast

- TNT equivalency
  - For situations that deviate from the reference case
  - Various test methods (blast, sand crush, pendulum)
  - By peak overpressure or impulse, or ability to crush a material
  - May also depend on the distance to the explosive

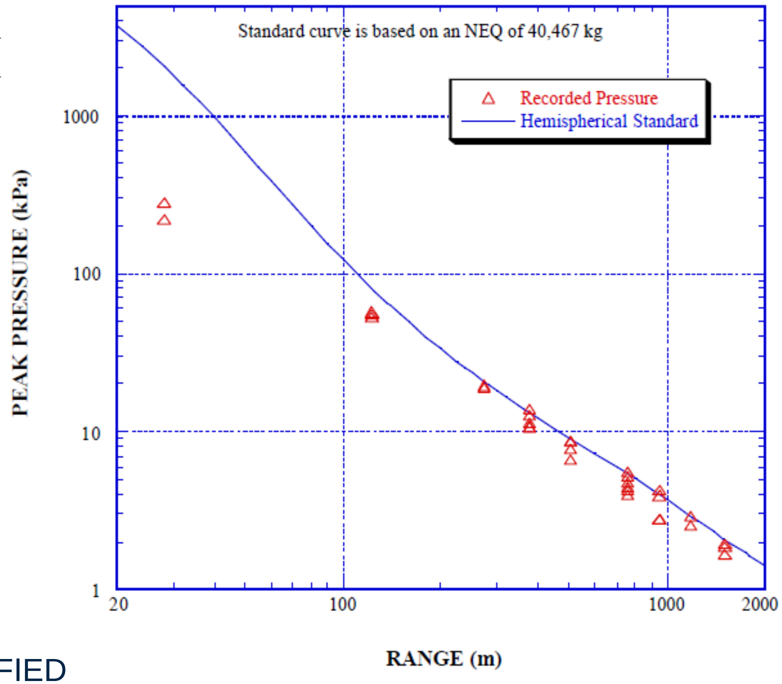
- Various factors that influence TNT equivalence
  - See table on next slide

External blast

Property		Reference case	Other examples / description
Energetic Material level	Energetic Material	TNT	RDX, C-4, black powder
	Additives	None	Aluminium particles
Boundary conditions	Charge shape	Hemispherical	Cubical, Rectangular, Line charge
	Geometry	Surface burst	Free air burst, complex geometry
	Surrounding medium	Air	Water
Initiation and response	Initiation location	Central	Side
	Initiation type	Initiator	Cook-off, Impact
	Energetic Material response	Detonation (I)	Partial detonation (II) Explosion (III), Deflagration (IV), Burn (V)
Munition level	Casing material	NA	Steel, Tungsten, Aluminium, DU
	Casing thickness	NA	Self-Explanatory
	Distributed charges	NA	Main charge, booster, rocket motor
Stack level	Stacking configuration	NA	Orientation (horizontal or vertical) and spacing
	Packaging	NA	Wood, cardboard
Storage level	Barriers	NA	Concrete
	Magazine construction	NA	Wall thickness, volume, reinforcement, venting
	Earth cover	NA	Earth cover thickness
	Barricade	NA	Barricade distance and height

External blast

- Simultaneous effect of multiple factors: 40 tonnes trial
  - 462 Mk82 bombs detonated in brick building
  - NEQ = 40,467kg Tritonal
  - Tritonal has TNT equivalency of 1.07
  - Reducing effect of bomb casing, storage structure
  - Overall effect:
    - yield substantially below 1
    - Yield dependent on distance (0.6 – 0.9



External blast

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	Additives	None	Aluminium particles
Boundary conditions	Charge shape	Hemispherical	Cubical, Rectangular, Line charge
	Geometry	Surface burst	Free air burst, complex geometry
	Surrounding medium	Air	Water
Initiation and response	Initiation location	Central	Side
	Initiation type	Initiator	Cook-off, Impact
	Energetic Material response	Detonation (I)	Partial detonation (II), Explosion (III), Deflagration (IV), Burn (V)
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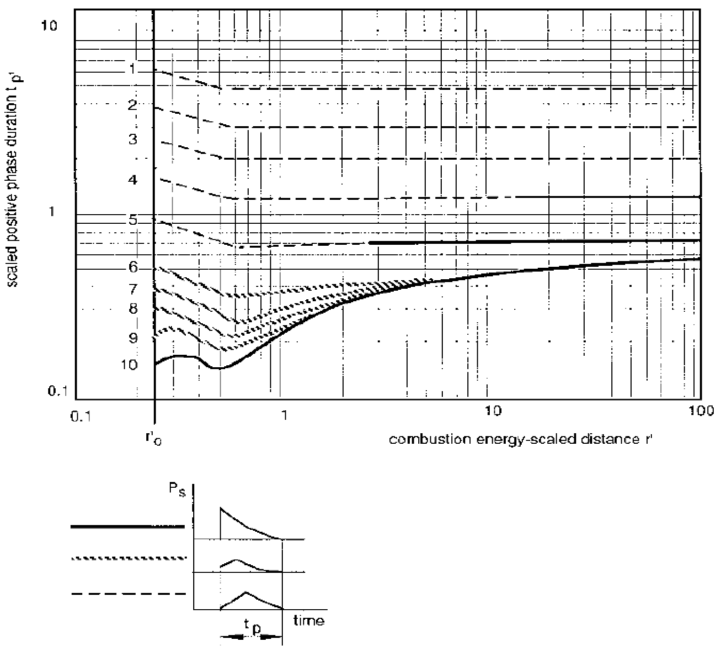
	Casing thickness	NA	Self-Explanatory
	Distributed charges	NA	Main charge, booster, rocket motor
Stack level	Stacking configuration	NA	Orientation (horizontal or vertical) and spacing
	Packaging	NA	Wood, cardboard
Storage level	Barriers	NA	Concrete
	Magazine construction	NA	Wall thickness, volume, reinforcement, venting
	Earth cover	NA	Earth cover thickness
	Barricade	NA	Barricade distance and height

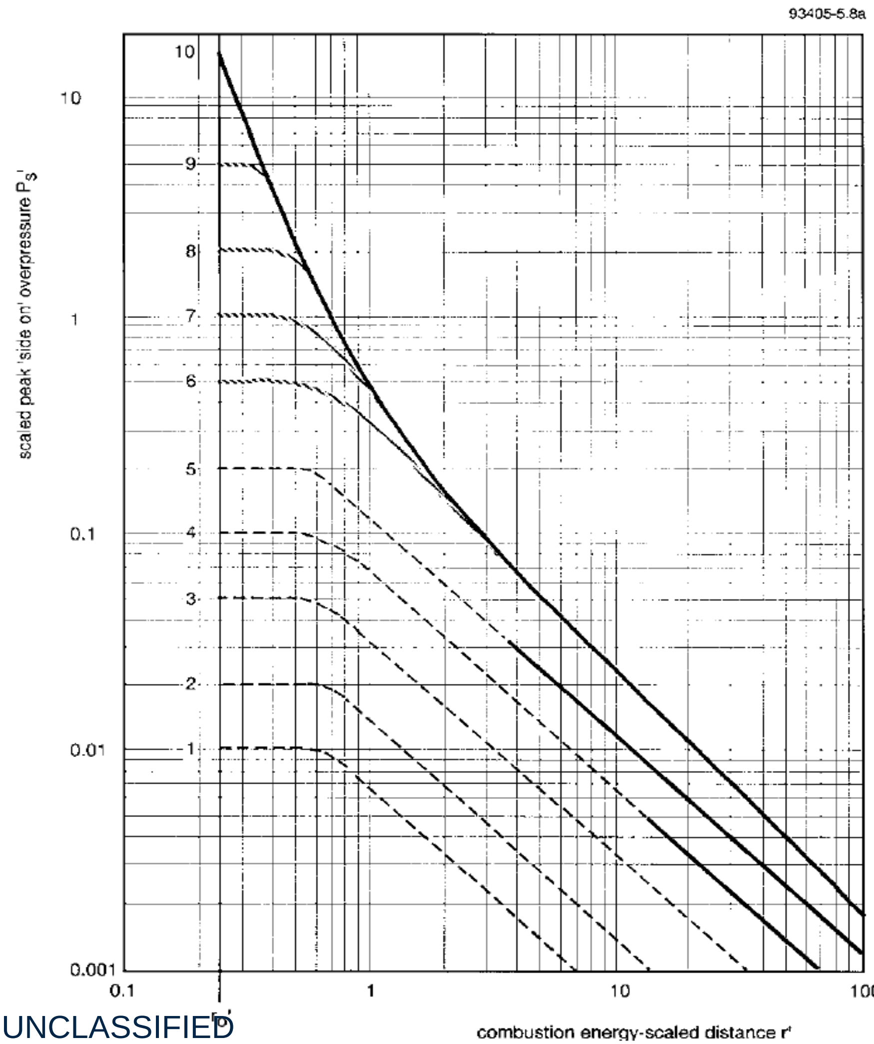
External blast

- What if response type is not a (full) detonation?
- Most appropriate: model that accounts for lower reaction rate and lower explosion overpressures
  - Multi-Energy (ME) method [Van den Berg, 2006].
  - Developed for gas explosions
  - Based on numerical simulation of a flame propagating at different speeds through hydrocarbon-air mixture
  - Model distinguishes between 10 different explosion overpressures
  - Charts for peak overpressure, impulse, positive phase duration, dynamic pressure

External blast

- Scaled peak overpressure and positive phase duration versus combustion-scaled distance

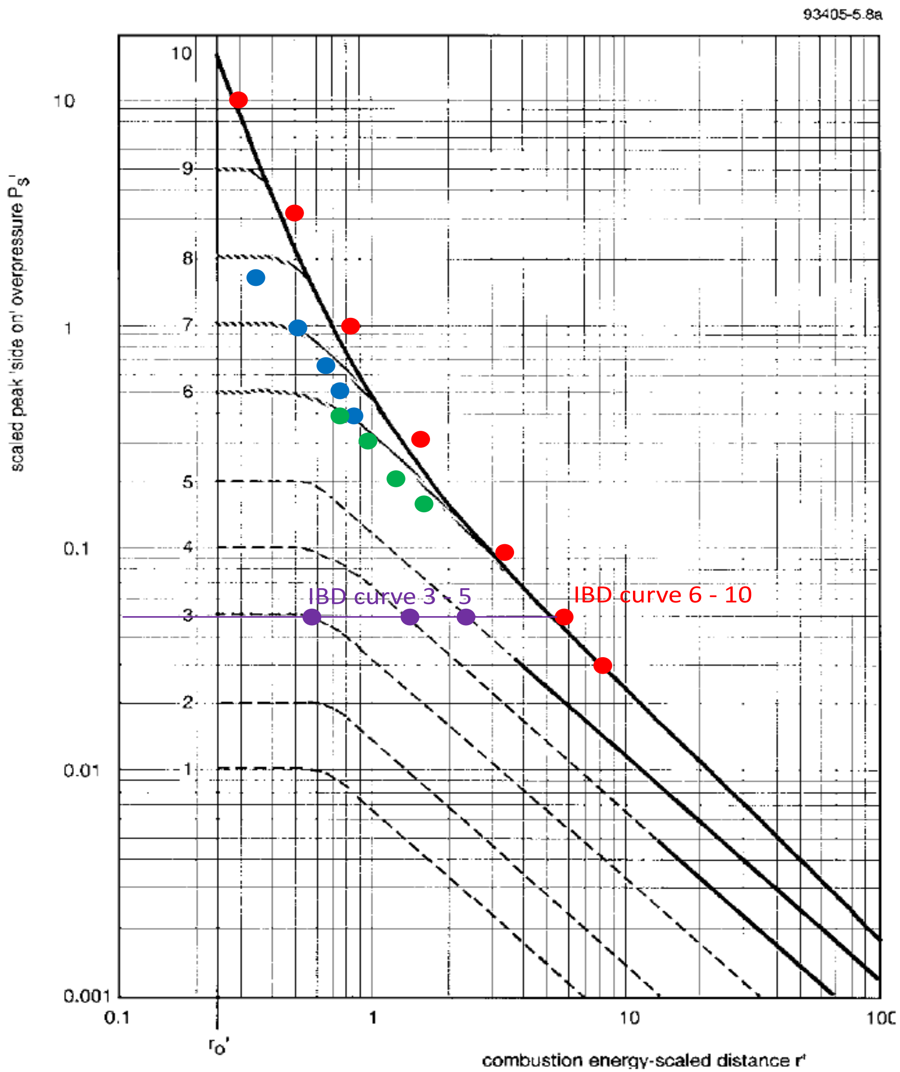




External blast

Comparison with:

- TNT blast (red)
    - Good match
- Pyrotechnic mixture (MTV) used in flares
    - 1.5 kg (green)
    - 12 kg (blue)
    - Curves not parallel
    - Better match with lower ME curves (e.g. 6 – 8)
- 5 kPa IBD level (purple)
    - Same distance for curve 6 – 8
    - Reduction for curve 3 - 5
    - Zero for curve 1 & 2



Conclusion (External blast)

- External blast will reduce in strength, representation by:
  - TNT equivalency
  - Models that account for a lower reaction rate and lower explosion overpressures

  - The potential of the Multi-Energy method (originally developed for gas-explosions) has been investigated

Recommendations

- Extension of standardized IM tests with a more detailed measurement of fragmentation and blast for the purpose of model validation

- Specification of more quantitative measures to help define the munition response in terms of reaction rate

- Focus on full scale testing of IM

Recommendations

- CFD and engineering models could focus more on fragmentation, internal and external blast for limited reactions rates.

- We hope that the findings in this paper will aid the development of Quantity Distances (QD) and risk management of future munitions for a range of responses

Questions?

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