MUNITION VULNERABILITY SIMULATION TOOLBOX

Gert Scholtes

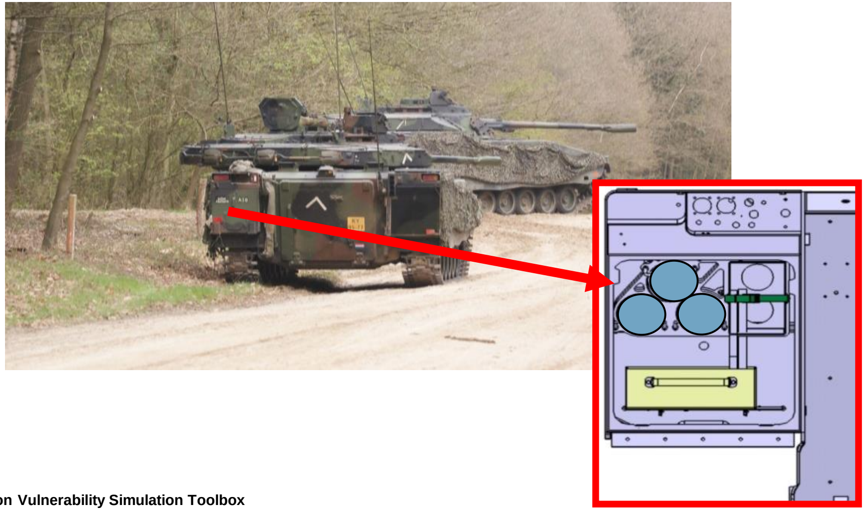
TNO innovation for life

OVERVIEW

- Background and approach
- Shock initiation modelling
- Validation and comparison
- Energy fluence E_c
- Influence of additional layer
- Future: Vulnerability toolbox / user interface
- Conclusions

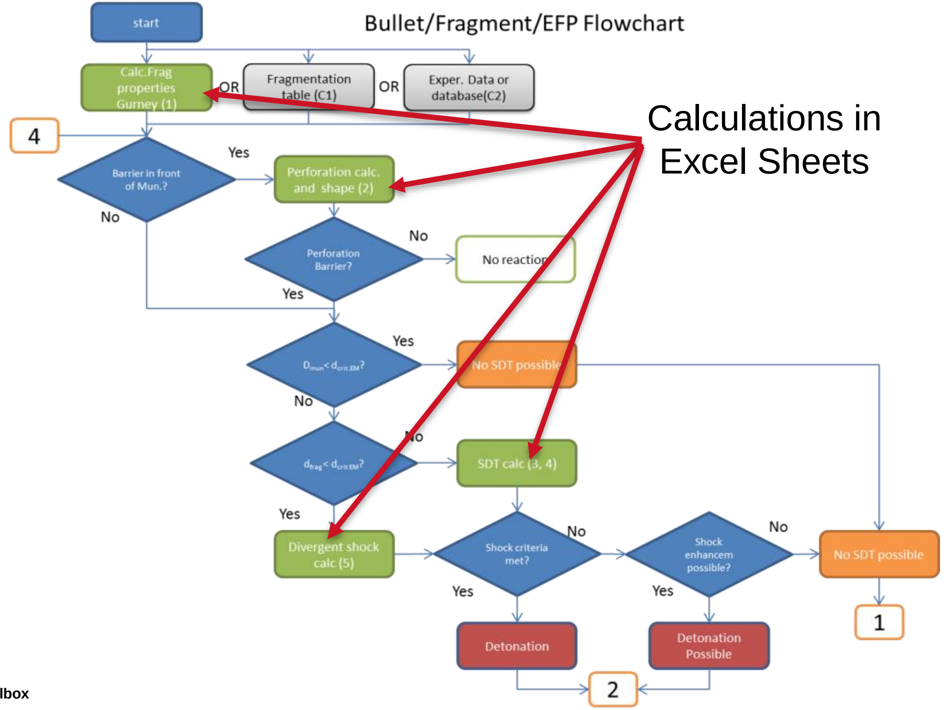
BACKGROUND AND APPROACH

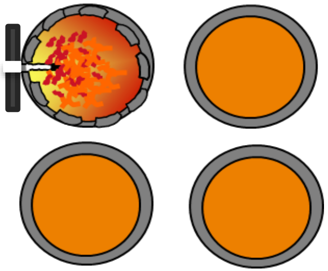
LIFE-CYCLE MUNITIONS - THREATS



- Fragments
- SCJ
- Bullets
- Cook-off
- Sympathetic reaction

TNO APPROACH
MUNITION VULNERABILITY TOOLBOX
THREAT – DONOR - ACCEPTOR





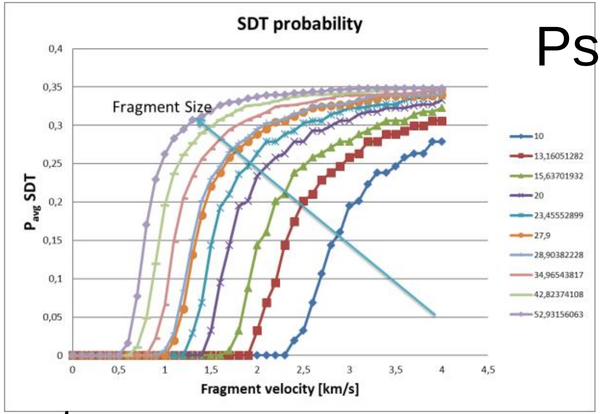
Spreadsheets/comments:

(1) Fragment velocity calculation with Gurney
(2) Perforation calculation using Thor equations
(3) SDT calculation Ec theory Haskins and Cook
(4) SDT calculation Green or Lundstrom
(5) Divergent shock calculation Green/Lundstrom
(6) EM heating due to penetration
(7) EM cook-off reaction calculation after penetration of bullet
(8) Pressurisation calculation after ignition and burning of EM
(9) Sympathetic reaction calculation confined stack and ono-on-one
(10) TNT equivalent blast/shock calculation
(C1) Fragmentation table of munitions (table #.#)
(C2) Fragmentation data from experiments or databases
(C3) Bullet and fragment test result database (e.g. BIRD or FRAID
(C4) SG table ref [#] tabel #.#
(C5) Cook-off database test results

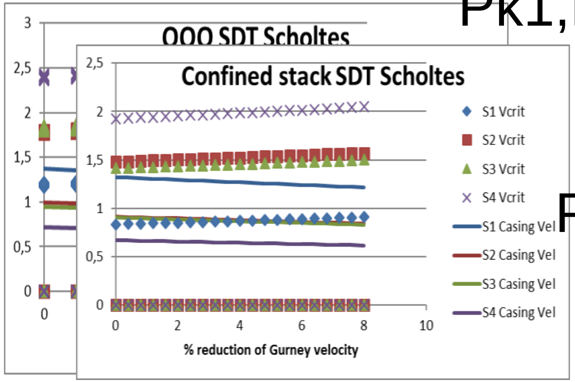
- Excel spreadsheet calculation
- Excel spreadsheet not implemented
- Excel spreadsheet (needs data)
- Data from database or Experiments
- Detonation reaction (possible)
- No Prompt shock detonation (SDT)
- Decision
- Reference Number 2

EXAMPLE: PROBABILITY OF A SR

Pk1,Pk2

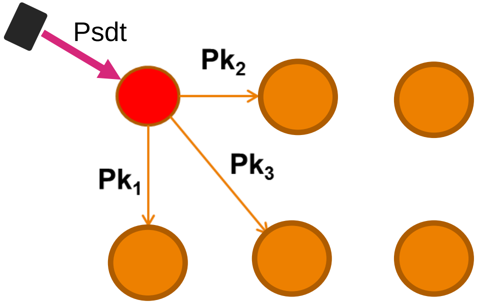


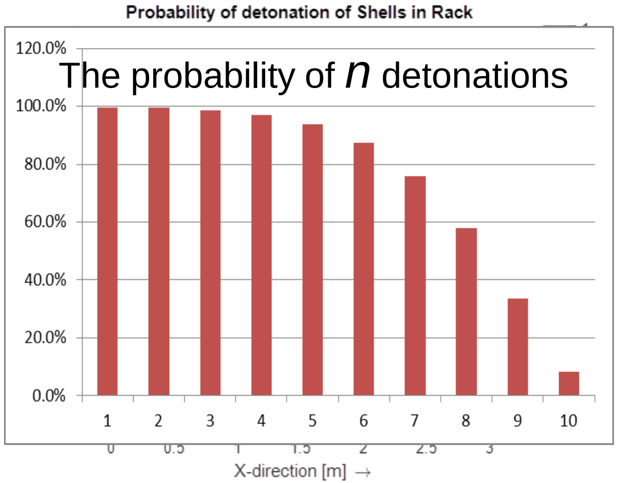
Psdt



Pk3

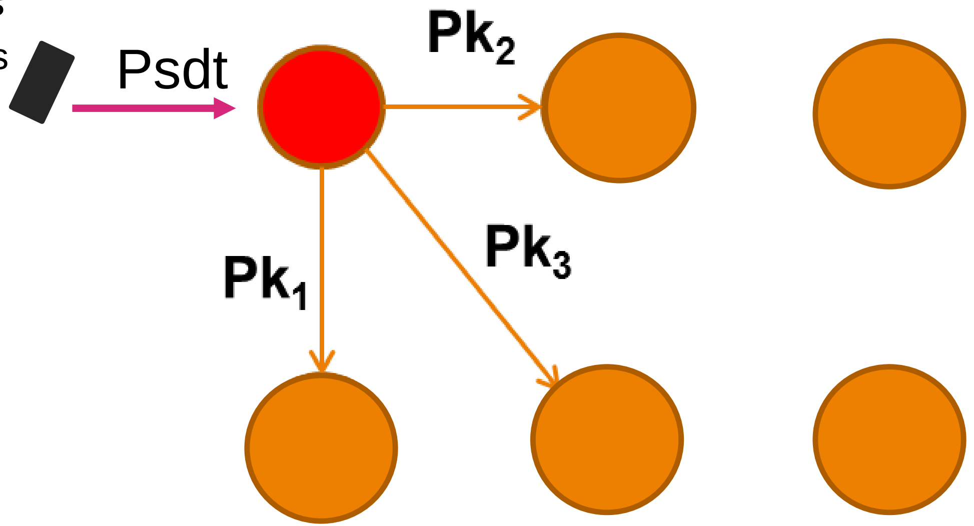
Fragment





SCENARIO - PROBABILITY

- E.g. missile hit: fragments travelling towards munition storage
- Probability: need for thousands of calculations
- Simple equation i.s.o. Hydro-code calculations



Need for good estimate of $V_{crit\text{-}frag}$ with Shock model

SHOCK INITIATION MODELLING

JACOBS-ROSLUND SHOCK MODEL: $V_{CRITICAL}$ FOR COVERED EXPLOSIVES

- Important parameters Required:
  - Fragment diameter ***d***
  - Thickness of casing ***t***
  - Sensitivity of Explosive ***A***

- ***Positive***
  - Data for many explosives
- ***Negative***
  - Only steel fragment and casing
  - No other layer e.g. Asphalt or PU liners

$$\begin{cases} V_1 = \dfrac{A}{d^{\beta}}(1+B)(1+C\dfrac{t}{d}) & \text{for } d > d_c \\ V_2 = \dfrac{E}{d^{\alpha}} & \text{for } d < d_c \end{cases} \quad (3)$$

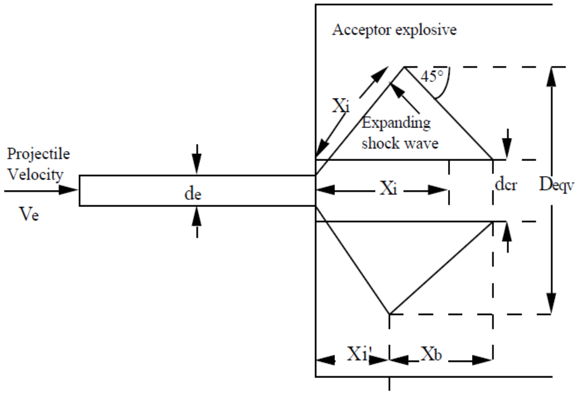
where $V_{threshold}$ = critical impact velocity for target detonation (mm/μs) = max (V_1, V_2)
d = fragment critical dimension e.g. diameter (mm)
β= exponent equal to ½ in the original equation
α = exponent added in a further improvement to the original formula
d_c = explosive critical diameter
t = target cover thickness (mm)
A = explosive sensitivity coefficient ($mm^{3/2}/\mu s$)

B = fragment shape coefficient (dimensionless)
B = 0 for flat ended cylinder
B = 1 for sphere
C = cover plate protection coefficient (dimensionless). C is different for blunt cylinders and spheres: $C_{sphere} = 1/3\ C_{cylinder}$.
E = explosive sensitivity second coefficient

GREEN SHOCK MODEL

- Uses pop-plot data of explosive; characteristic data P1 and S (run distance to detonation) and critical diameter of explosive
- Method: what pressure Pe will lead to a detonation due to shock wave having a diameter >= Dcrit, detonation at depth X, in the explosive
- Also model when Diameter impactor < Dcrit, explosive

$$X = 10\left(\frac{P_1}{P_e}\right)^S$$



- ***Positive***
  - Relative large database for different explosives
- ***Negative***
  - Results do not always connect (range Dfrag<Dcrit,expl with Dfrag> Dcrit,expl)
  - Not for spheres or oblique impact

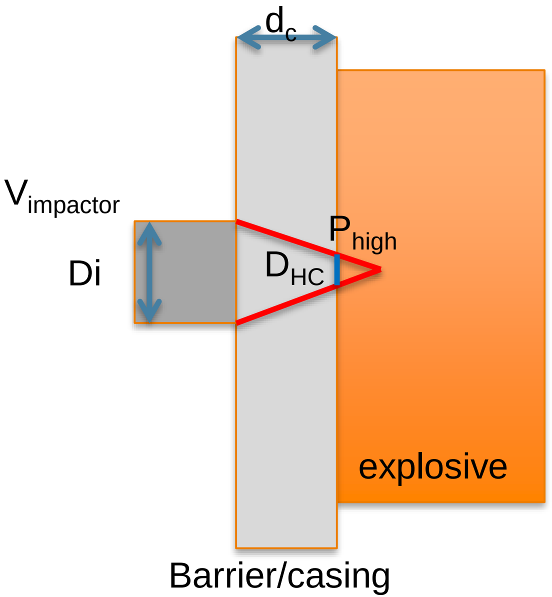
OLD JAMES, HASKINS AND COOK BASED ON E_c

$$E = \int P \cdot u_{p,x} \cdot dt \quad \text{or} \quad E_c = P u_p T$$

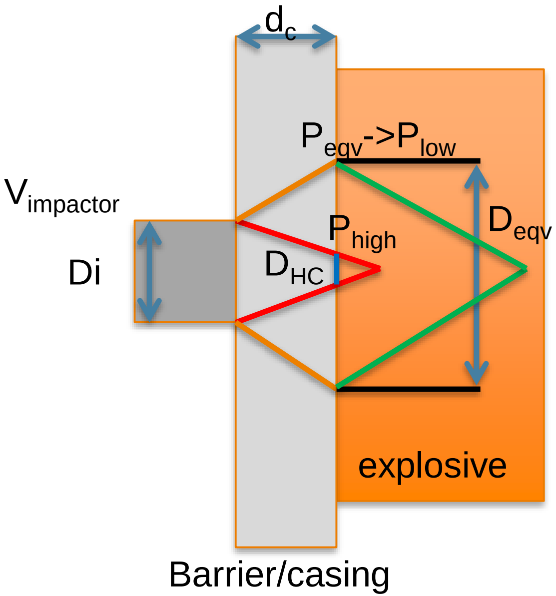
$$T = \frac{R_c}{3c} \qquad E_c = \frac{P u_p R_c}{3c}$$

- Uses shock Hugoniots and Ec for sensitivity of explosive, diameter and velocity fragment
- (T= shock duration, u_p particle velocity P the pressure
- Pressure and particle velocity u_p depend on fragment velocity and shock hugoniots of materials
- Method: solve Vcrit for $E_{frag}=E_c$

- ***Positive***
  - Model can be used for all kind of cover materials
  - Also for spheres or oblique impact
  - One value of E_c
- ***Negative***
  - Not always correct value (high velocities)
  - Does not work if Dfrag<2*Dcasing (thickness)



NEW SHOCK MODEL: COMBINATION OF JH&C AND P_{EQV} IDEA OF GREEN→ E_{FLUX}



Energy Fluence: $E = \int P \cdot u_{p,x} \cdot dt$

With: P= pressure in the explosive, Up Part. Velocity of explosive and *t* the time of the shock duration

For explosive $E_{impactor} \geq E_{crit,exp}$ → Detonation

- Solving impedance matching equations for projectile→ barrier→ explosive

$$E_{total} = \frac{\{ E_{expanding}\ \pi\ [\ (D_{eqv}/2)^2 - R_c^2\ ] + E_{H\&C}\ \pi\ R_c^2\}}{\{\ \pi\ (D_{eqv}/2)^2\ \}}$$

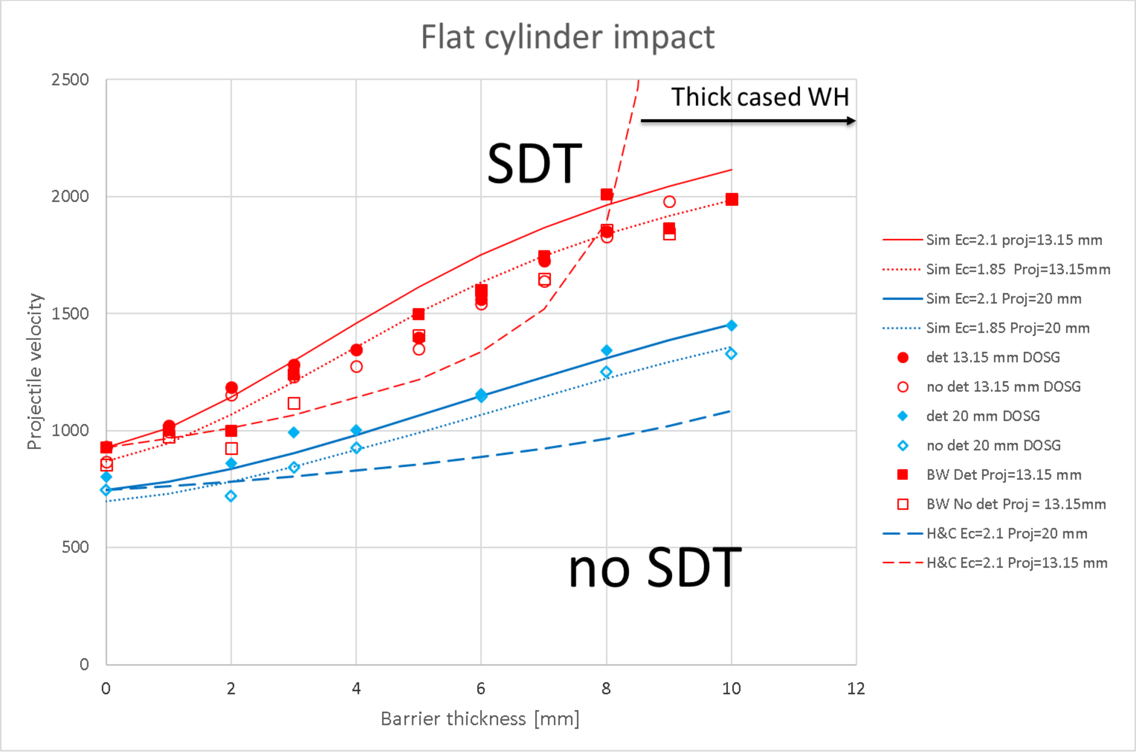
$E_c = E_{total}$

- Solving equation → $V_{critical,\ projectile}$

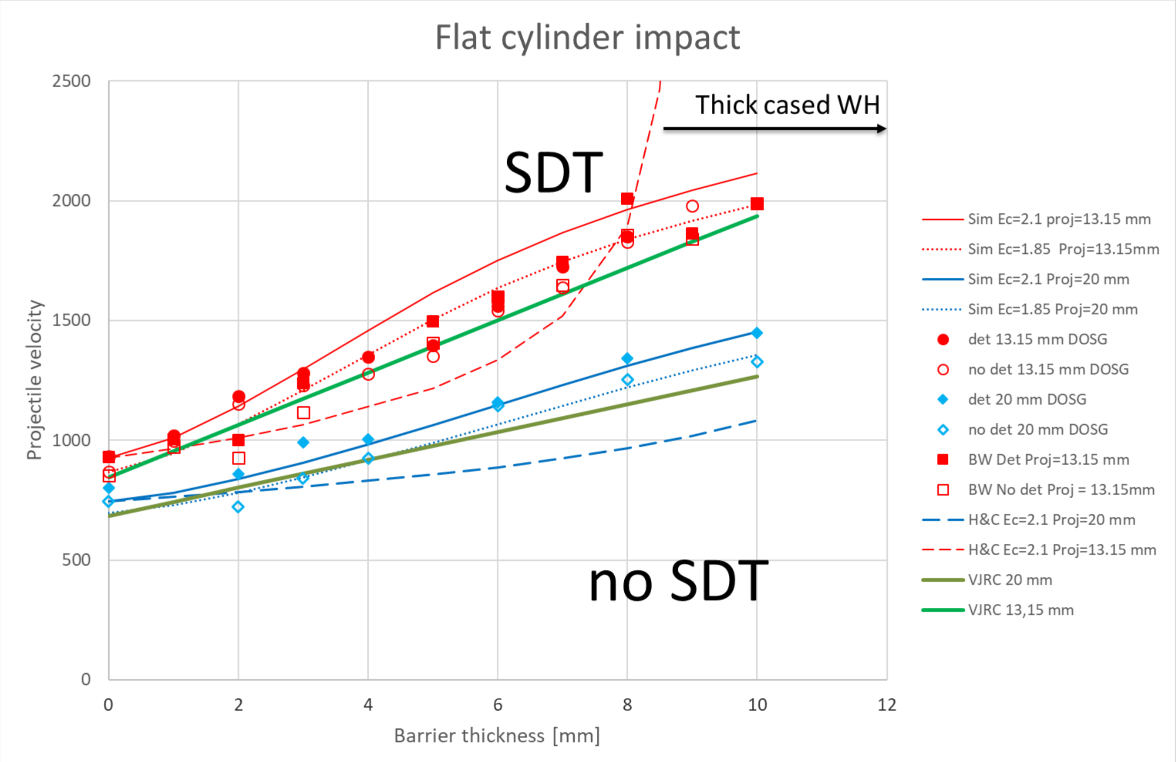
VALIDATION AND COMPARISON

VALIDATION WITH DATA FROM LITERATURE (EXAMPLE: COMPOSITION B)

- Value Ec influenced by type of study:
  - Vulnerability or
  - Lethality

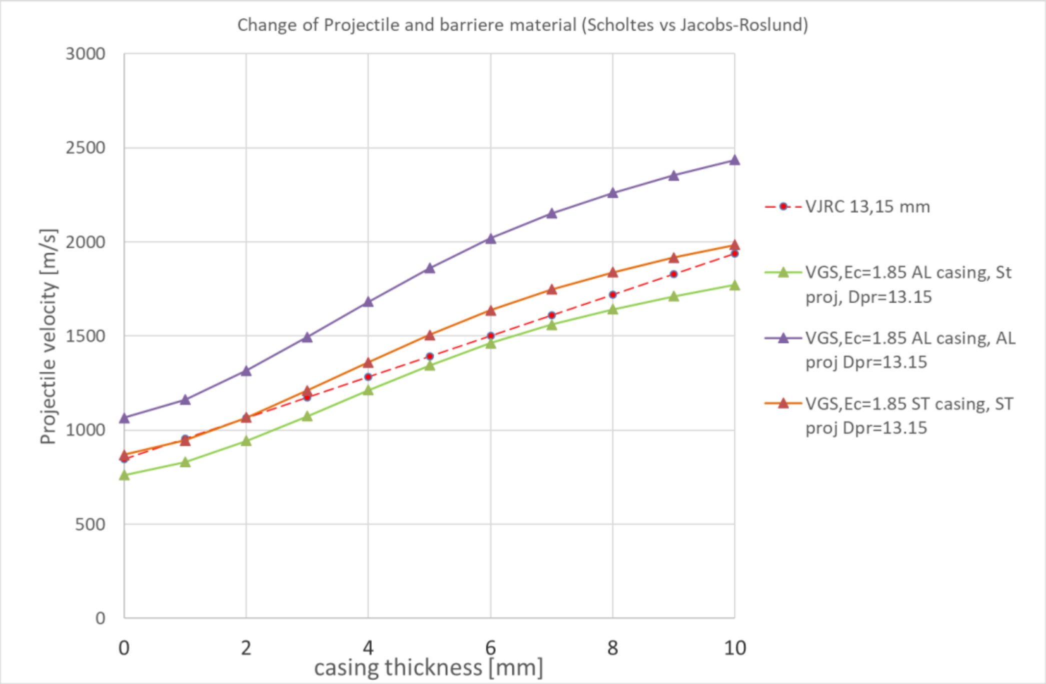


EXPERIMENTAL VS. JR VS. H&C VS. SCHOLTES



WHY JACOBS-ROSLUND NOT ALWAYS GOOD OPTION?

- Comp B: Steel proj, steel casing
- Comp B: steel proj, Aluminium casing
- And what if:
- Comp B: Alum proj. and Alum casing?

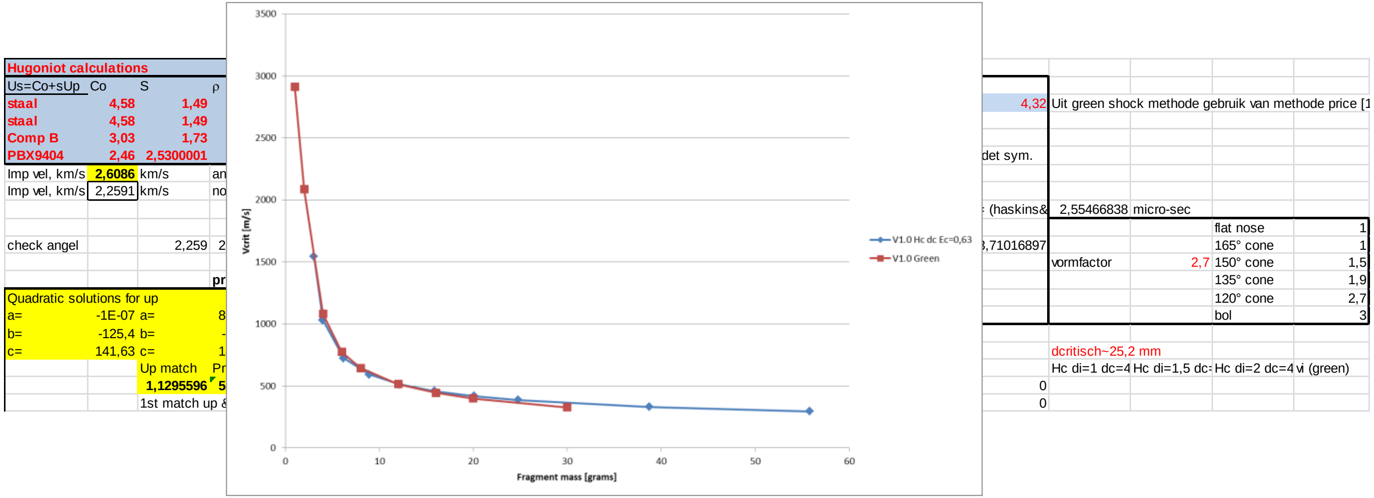


ENERGY FLUENCE E_c

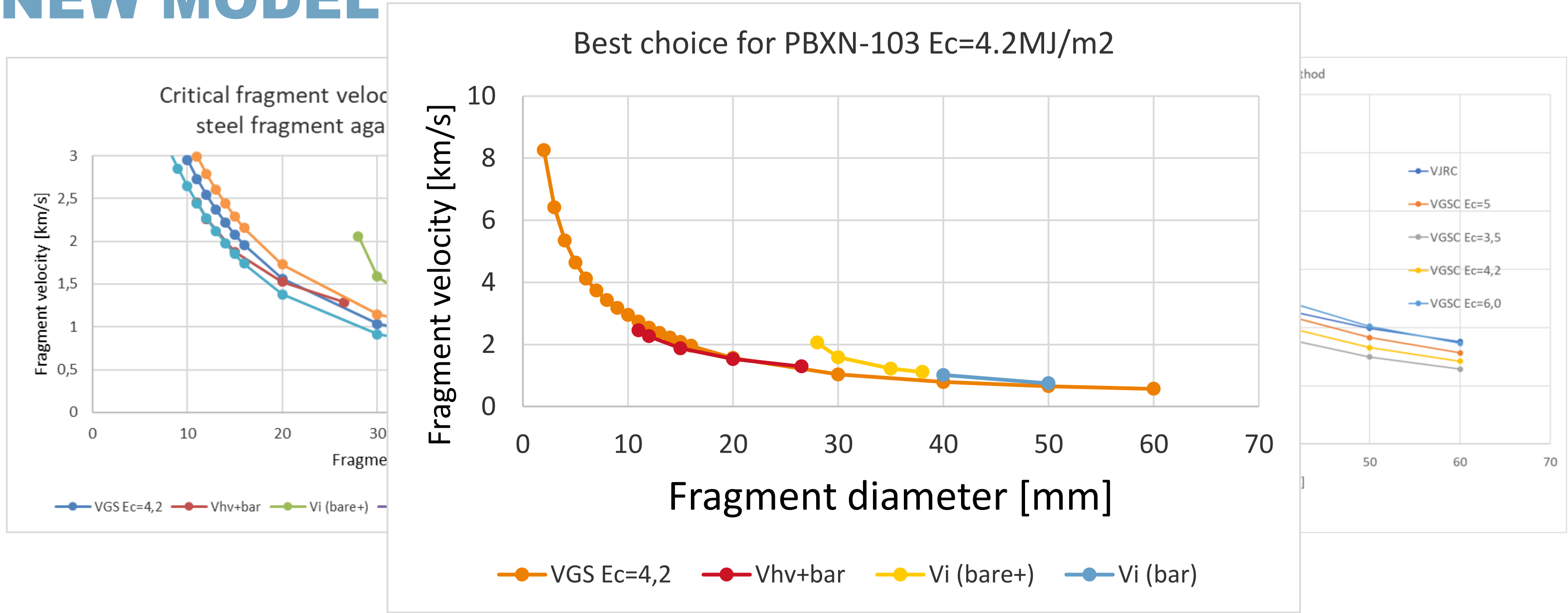
ESTIMATION OF VALUE OF E_c : COMPARISON WITH OTHER MODELS

- Haskins and Cook use Critical Energy criteria Ec (shock mechanics)
- Green/Lundstrom uses critical diameter Dc of explosives and Run-distance to detonation criteria:
  - With P1 and S the characteristic parameters of an explosive

$$X = 10\left(\frac{P_1}{P_e}\right)^S$$

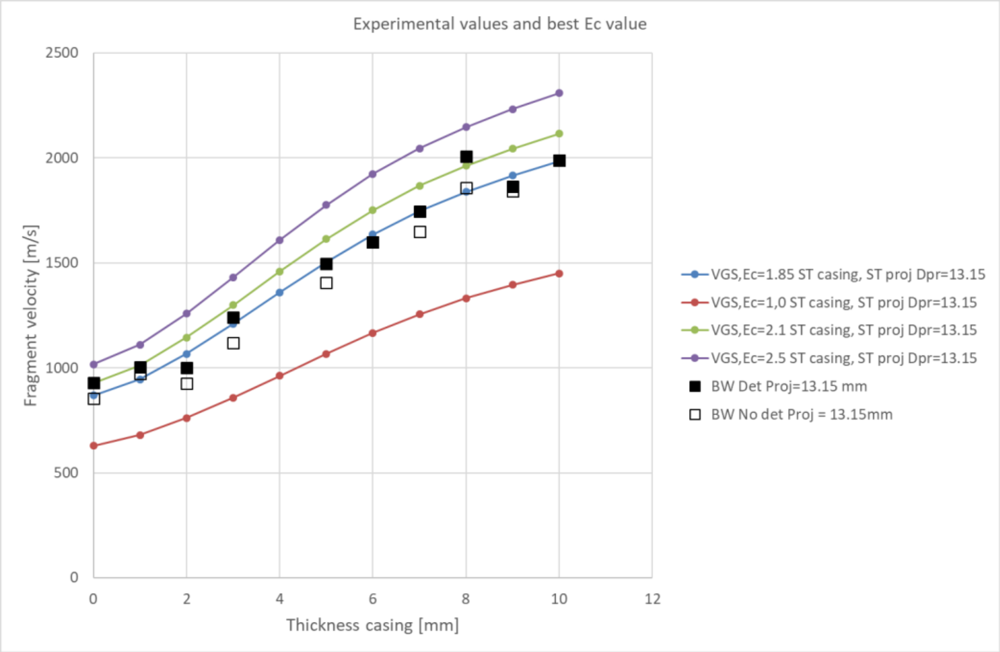


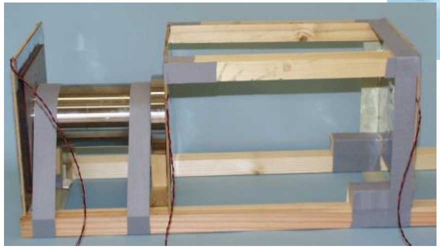
EXAMPLE PBXN-103; GREEN AND JR VERSUS NEW MODEL



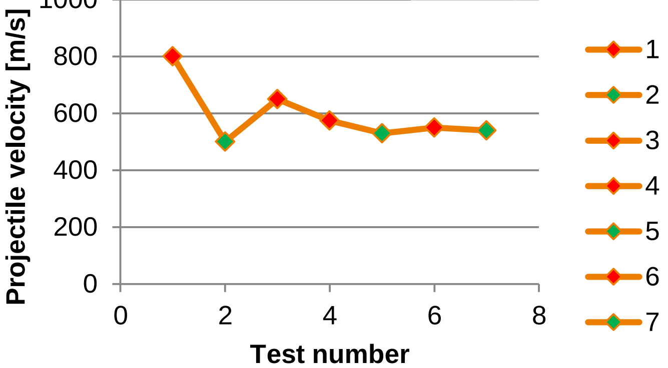
EXPERIMENTS: V_{CRIT} AS FUNCTION OF PROJECTILE DIAMETER OR BARRIER THICKNESS

- From experiments estimation of critical Energy (fluence) Ec





Test #	Proj V	Reaction
1	800	Detonation
2	500	no-D
3	650	D
4	575	D
5	530	no-D
6	550	D
7	540	no-D



NEW METHOD FOR E_c: REACTION ZONE LENGTH δ

$$E_c = \frac{\rho_o D_j \delta \left[\frac{D_j - a_x}{2b_x} + \frac{D_j}{2(r+1)} \right]^2}{D_j - \left(\frac{D_j - a_x}{2b_x} + \frac{D_j}{2(r+1)} \right)} \qquad ^{1)}$$

- Shock Hugoniot of material: $U_s = a_x + b_x U_p$
- D_j=detonation velocity
- r = Specific heat ratio
- ρ_0 = density of explosive
- δ = length of reaction zone→ to be determined

[1]) *H.S. Yadav, S.N. Asthana, and A. Subhananda Rao,*
Critical Shock Energy and Shock and Detonation Parameters of an Explosive
Defence Science Journal, Vol. 59, No. 4, July 2009, pp. 436-440

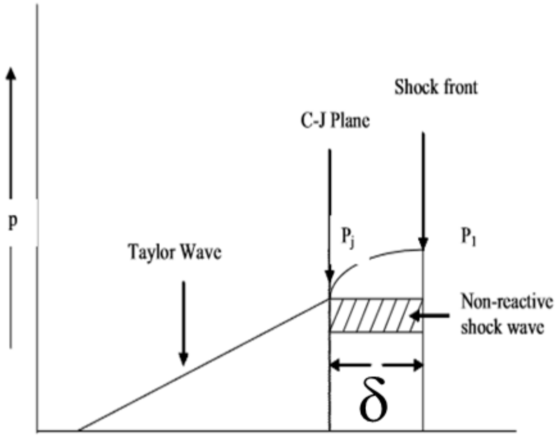


Table 3. Comparison of calculated and reported values of critical shock energies of different explosives

S.No.	Explosive	Density g/cc	Critical shock energy Ec, J/cm²		Reference No.
			Calculated	Reported	
1.	RDX/TNT (60/40)	1.72	201.80	190.0	4
2.	TNT	1.54	83.50	77.0	4
3.	HMX	1.77	153.89	150.0	2
4.	RDX	1.60	174.30	175.0	2

REACTION ZONE MEASUREMENT USING SHOCK INDUCED POLARIZATION [1])

- Works good up to pressures of 25 GPa in Plexiglas, but maybe other materials can be used

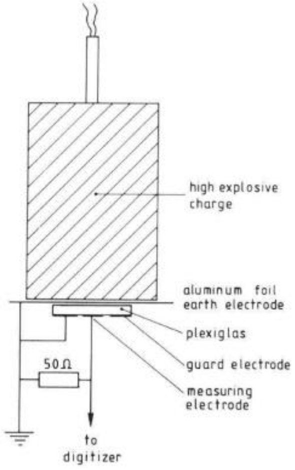


Fig. 1. Setup of shock-induced polarization experiments behind high explosives.

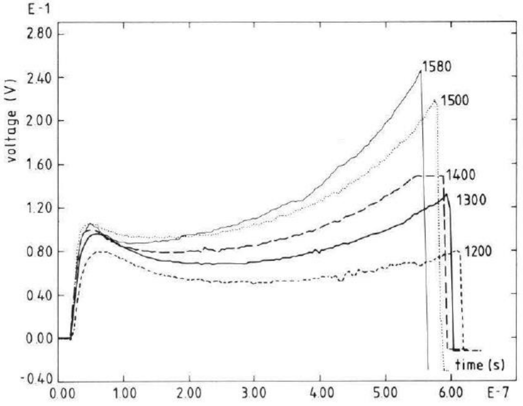


Fig. 5. SIP signals from 3 mm Plexiglas behind TNT charges pressed to five different densities (indicated in kg/m³).

TABLE I

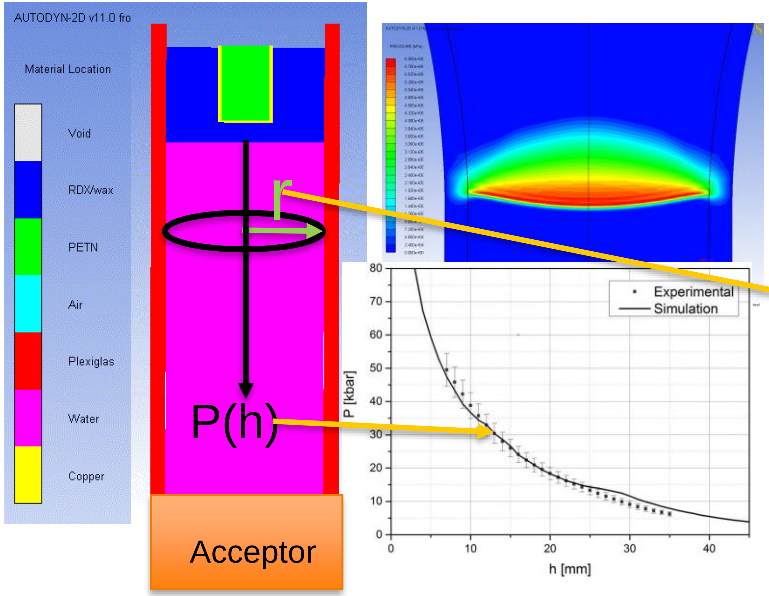
Reaction Zone Parameters and Detonation Velocity for Pressed TNT Charges of Various Densities

Density (kg/m³)	Reaction Time (ns)	Detonation Velocity (m/s)	Reaction Zone Length (mm)
1200	251	5300	0.93
1300	205	5700	0.82
1400	134	6240	0.59
1500	110	6490	0.50
1580	81	6830	0.39

[1])*R. R. IJsselstein, Reaction zone measurements in high explosive detonation waves by means of shock-induced polarization", Combustion and Flame, 66 (1986) 27-35*

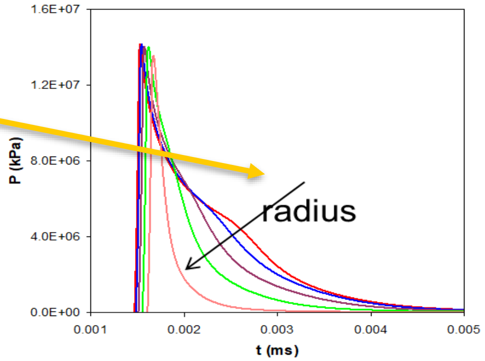
E_c FROM GAP TEST RESULTS (STANAG 4488)

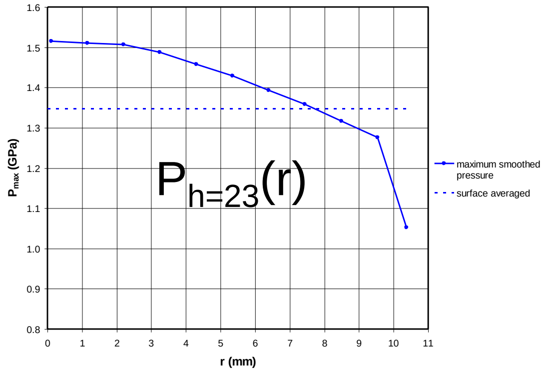
- Two papers looked at relation of Ec and 21 and 50 mm GAP-test results
- Simulation: Pressure at central axis should follow the “calibration curve” as function of gap length *h*



Surface averaged max. Pressure

$$\overline{P_{max}} = \frac{1}{\pi R^2} \int 2\pi r P_{max}(r)\, dr$$



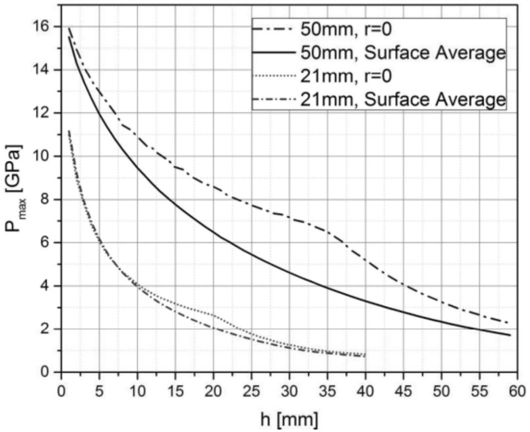


*) 1) Ries Verbeek, Richard H. B. Bouma. “Evaluation of the Energy Fluence in the Small Scale Gap Test”, PEP 2011, 36
2) Sebastian Wurster, “Evaluation of the James Initiation Criterion in the 21 mm and 50 mm PMMA Gap Test”, PEP 2017, 42

CALCULATION OF ENERGY FLUENCE AS FUNCTION OF GAP LENGTH *h*

$$E = \int \overline{P_{max}} \cdot u_{p,x} \cdot dt$$

- Example: in 21 mm gap test a P of 6.25 Gpa → Ec=4 MJ/m2



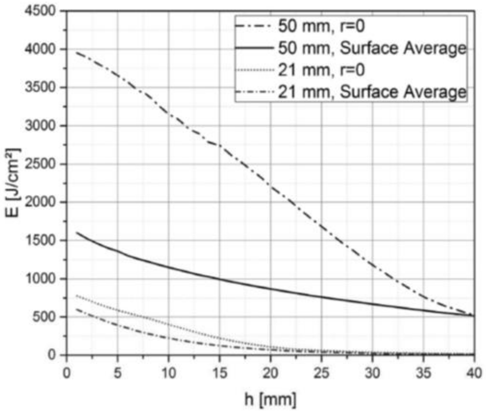


Figure 6. Axial and surface averaged energy fluences as a function of gap length for the 21 mm and 50 mm PMMA gap test.

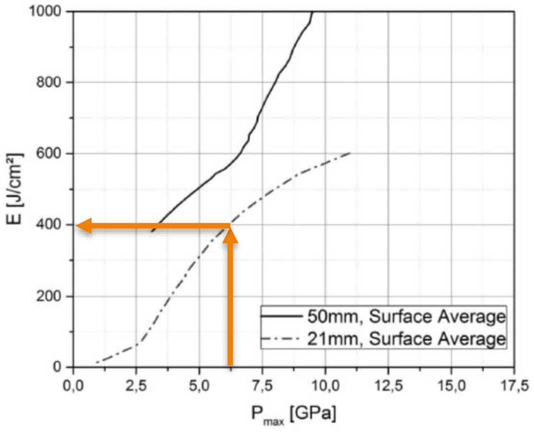
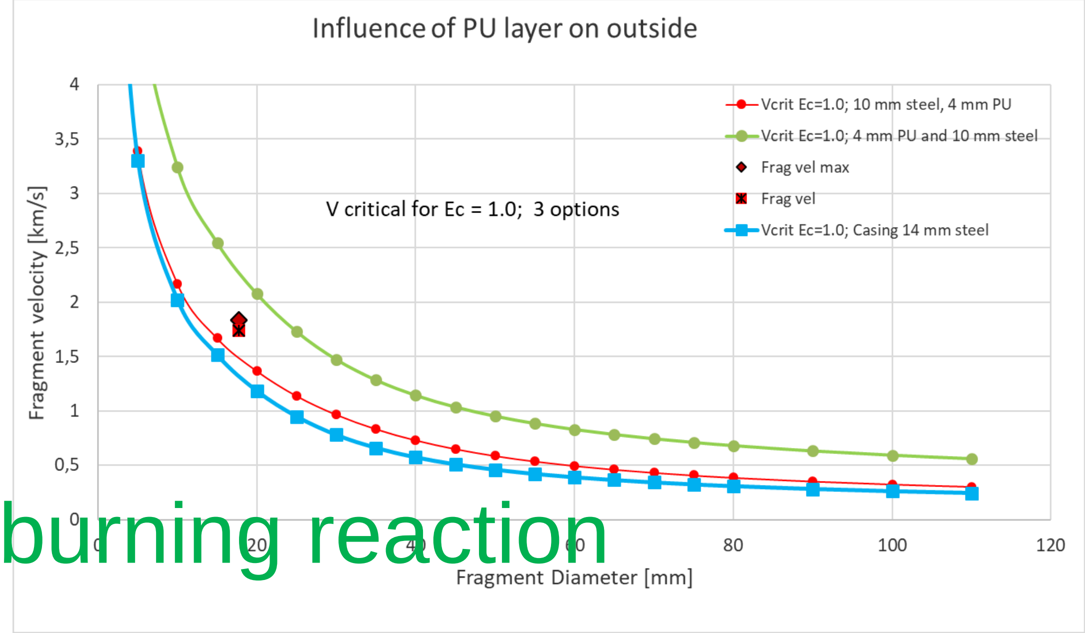


Figure 8. Surface averaged energy fluence as a function of maximum axial pressure in the 21 mm and 50 mm gap test.

NEW MODEL: INFLUENCE OF ADDITIONAL LAYER

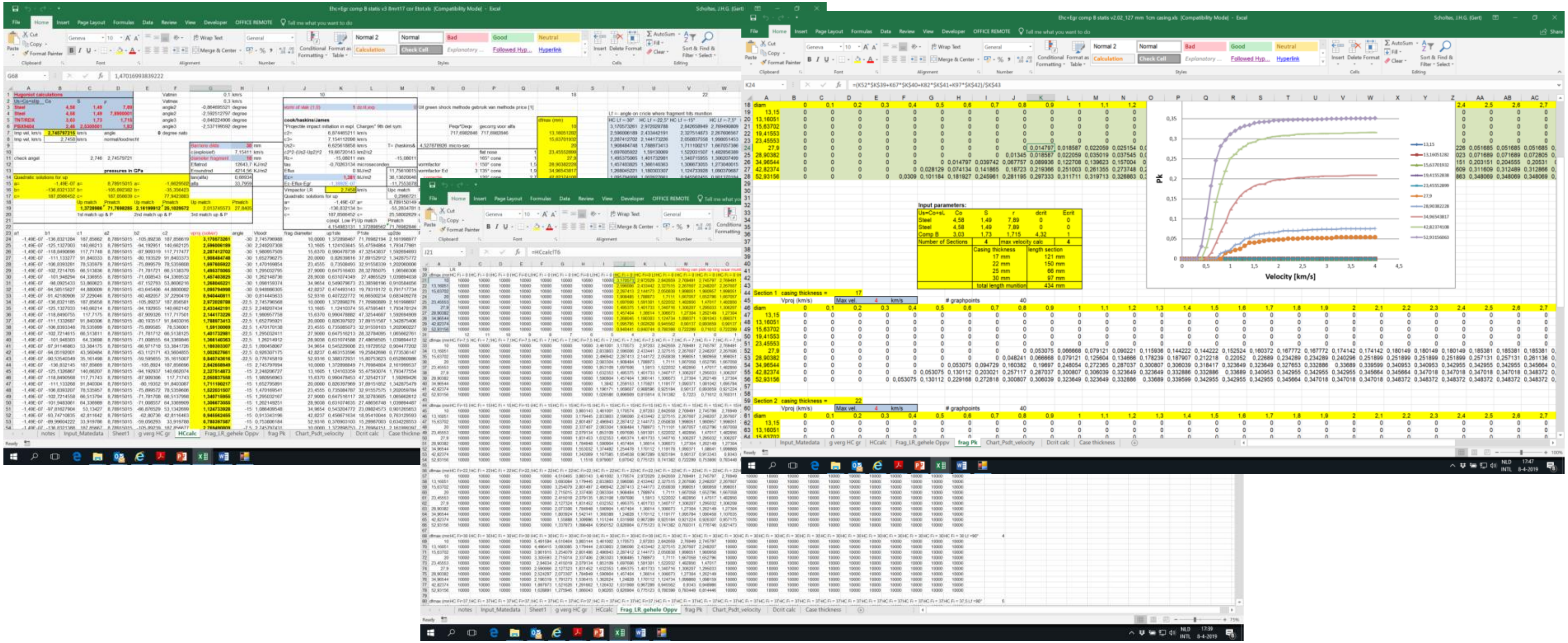
- Advantage of new model: possibility of additional layer! .e.q PU or asphalt
- Fragment impact on warhead casing 14mm
- 18 mm steel fragment V~ 1800 m/s
  - 1) 14 mm steel casing
  - 2) 10 mm casing with 4 mm PU
  - 3) 4mm PU in front of 10 mm Steel



Experiments: slow burning reaction

FUTURE:
VULNERABILITY TOOLBOX / USER INTERFACE

MANY CALCULATIONS IN SPREADSHEETS → SOURCE FOR ERRORS

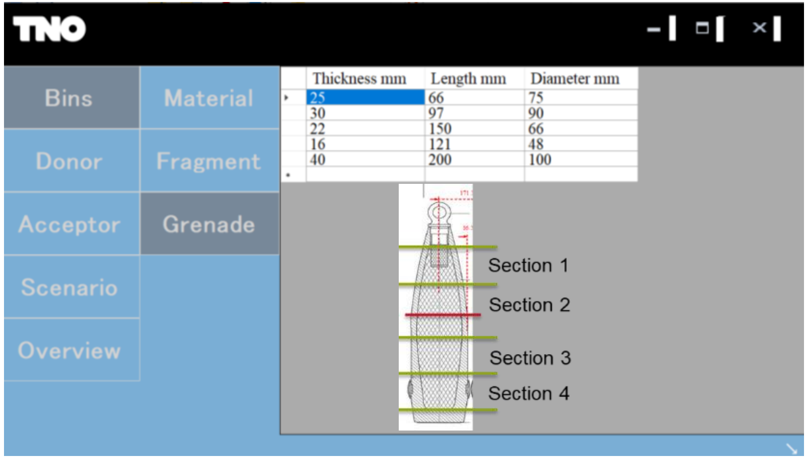


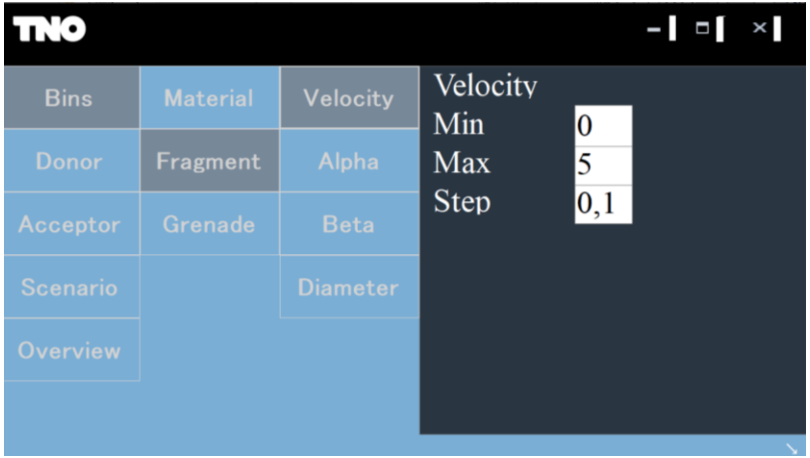
USER INTERFACE

- Input:
  - Scenario
  - Type of munition (incl. sections, materials, sizes and distances, errors)
  - Model used for SDT calculation (single fragment) . Conf. stack, O-O-O calculation etc.

- Calculations: drivers/codes for SDT calculation, conf. stack calculation, storage calculation etc.

- Output: Single fragment output, Storage situation output, Multiple fragment output……





CONCLUSIONS

- Improved shock model works very well; follows experimental curves
- New model has several advantages
  - Simple and fast calculations using E_c and shock hugoniots of materials
  - Multi layer target; any material
  - Also spherical impactor or oblique impact
  - Can be used in Statistical toolbox for probability calculations
- Several options to estimate E_c for “unknown” explosives
- Tool will be implemented in platform vulnerability codes (TARVAC and RESISTS)

Results will contribute to reduction of risks in general and of munitions storage and more balanced ship/vehicle design.

THANK YOU FOR YOUR ATTENTION

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