Materials Behaviour under Impact

Materials Behaviour and Evaluation of Protection Potential

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Materials Behaviour under Impact

Part 1

Evaluation of Ballistic Results

Part 2
High Dynamic Loading of Materials

Outline

Part 1

Evaluation of Ballistic Results

Introduction

Perforation and Penetration

Ballistic Limit and Tate Equation

Depth of Penetration (DoP)

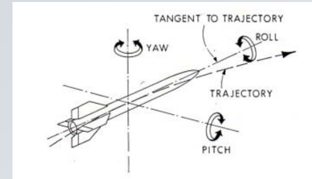
Equivalence and Effectiveness Factor

Failure of Materials

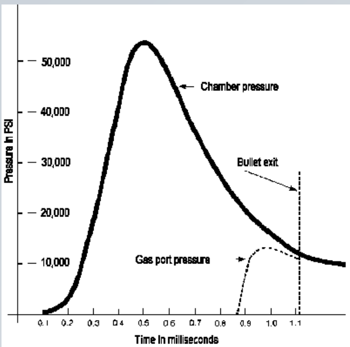
Ballistic

Institute of
Shock Physics

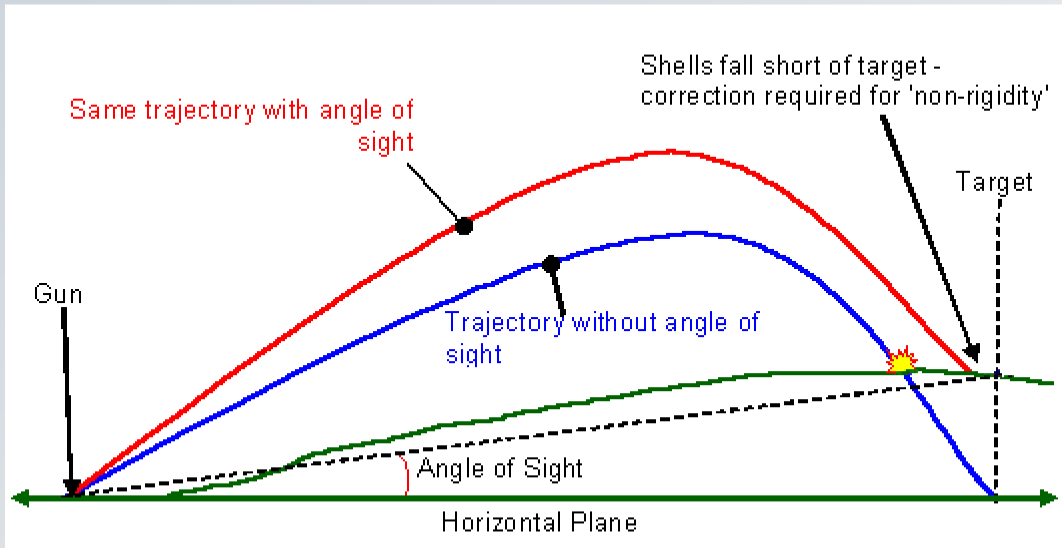
External ballistic
from gun to target



Internal ballistic



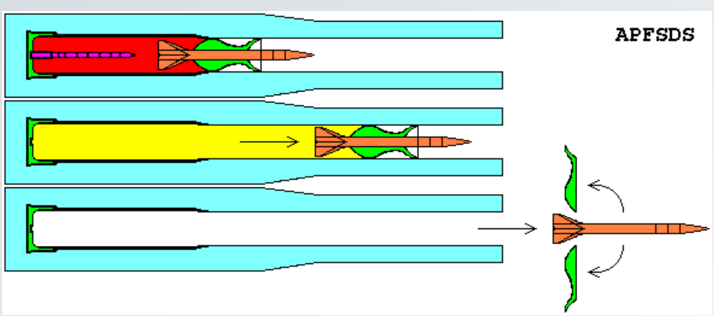
Acceleration of a projectile



Terminal ballistic

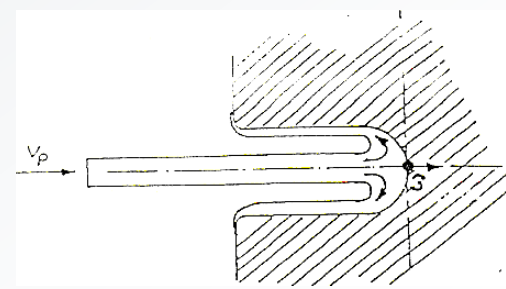
Interaction projectile/target

materials/materials



Transitional ballistic

Projectile leaves the muzzle
Interaction with the muzzle



Terminal Ballistic Tests

Penetration

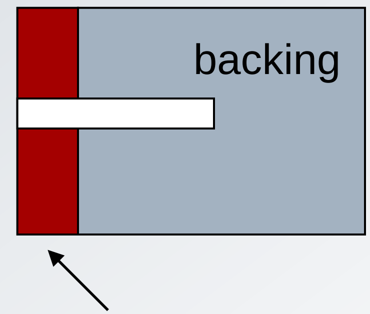
DoP *(depth of penetration)*
residual penetration in
semi infinite target

Information about:

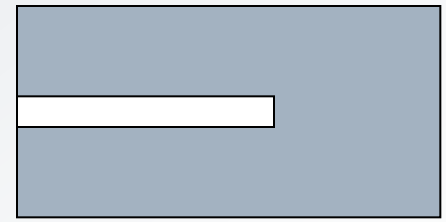
➔ *max. ballistic protection potential*

➔*direct comparison of materials*

„materials ranking“



studied material



Reference target

(*same material as backing*)

Terminal Ballistic Tests

Perforation

Realistic target design

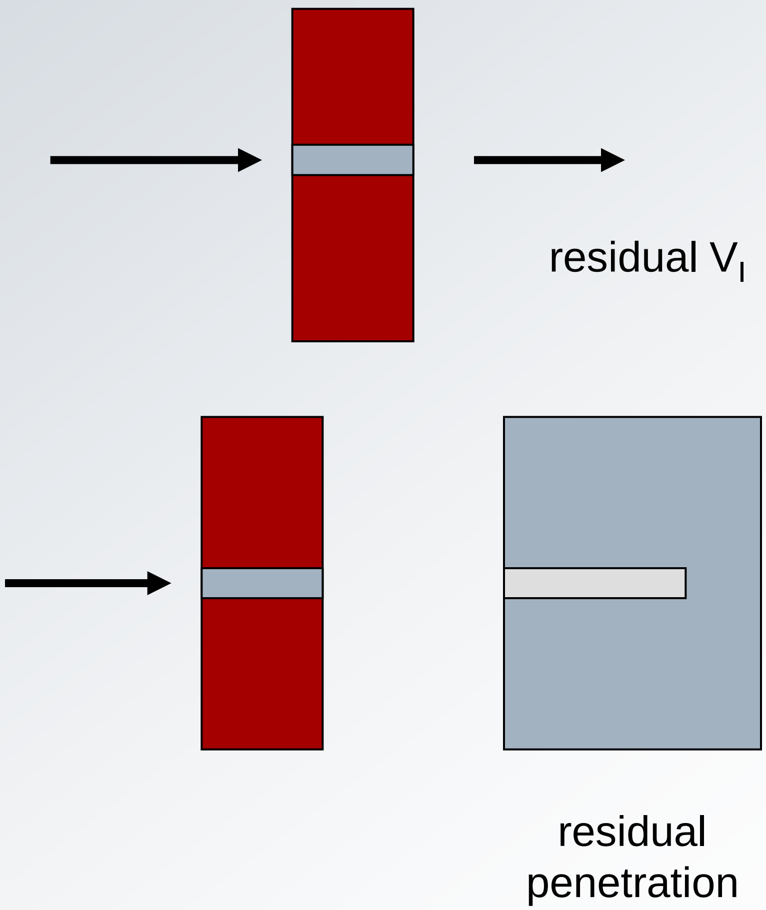
Ball. Limit velocity

Residual velocity

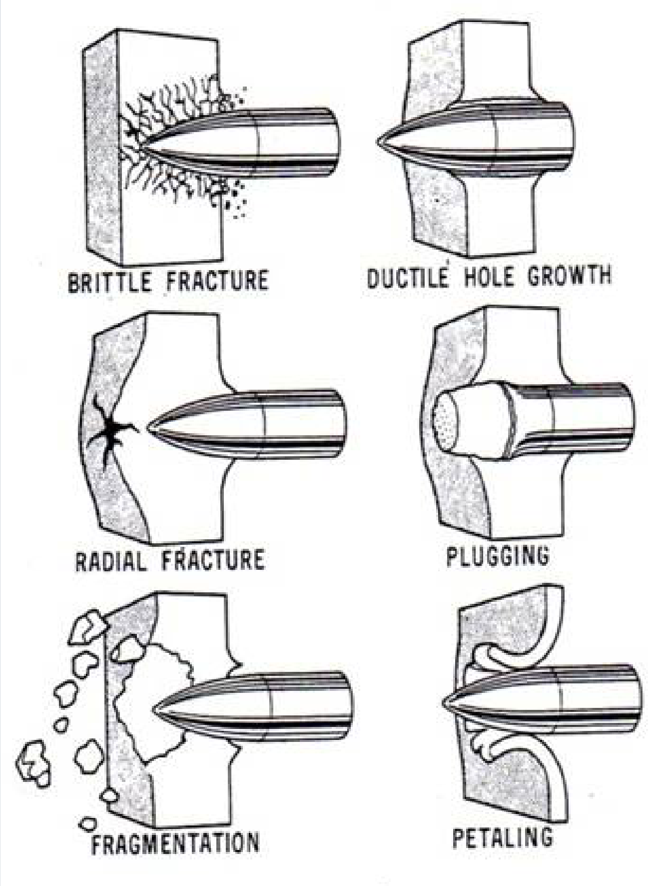
Information about:

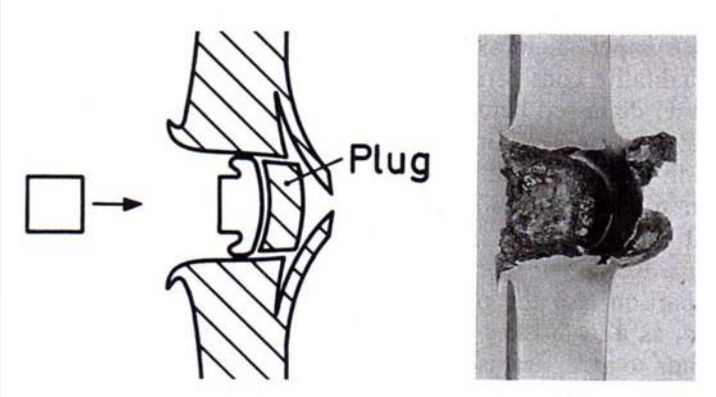
➔ *effective ballistic protection potential*

➔ *information concerning realistic mass of a target, mass of the system*

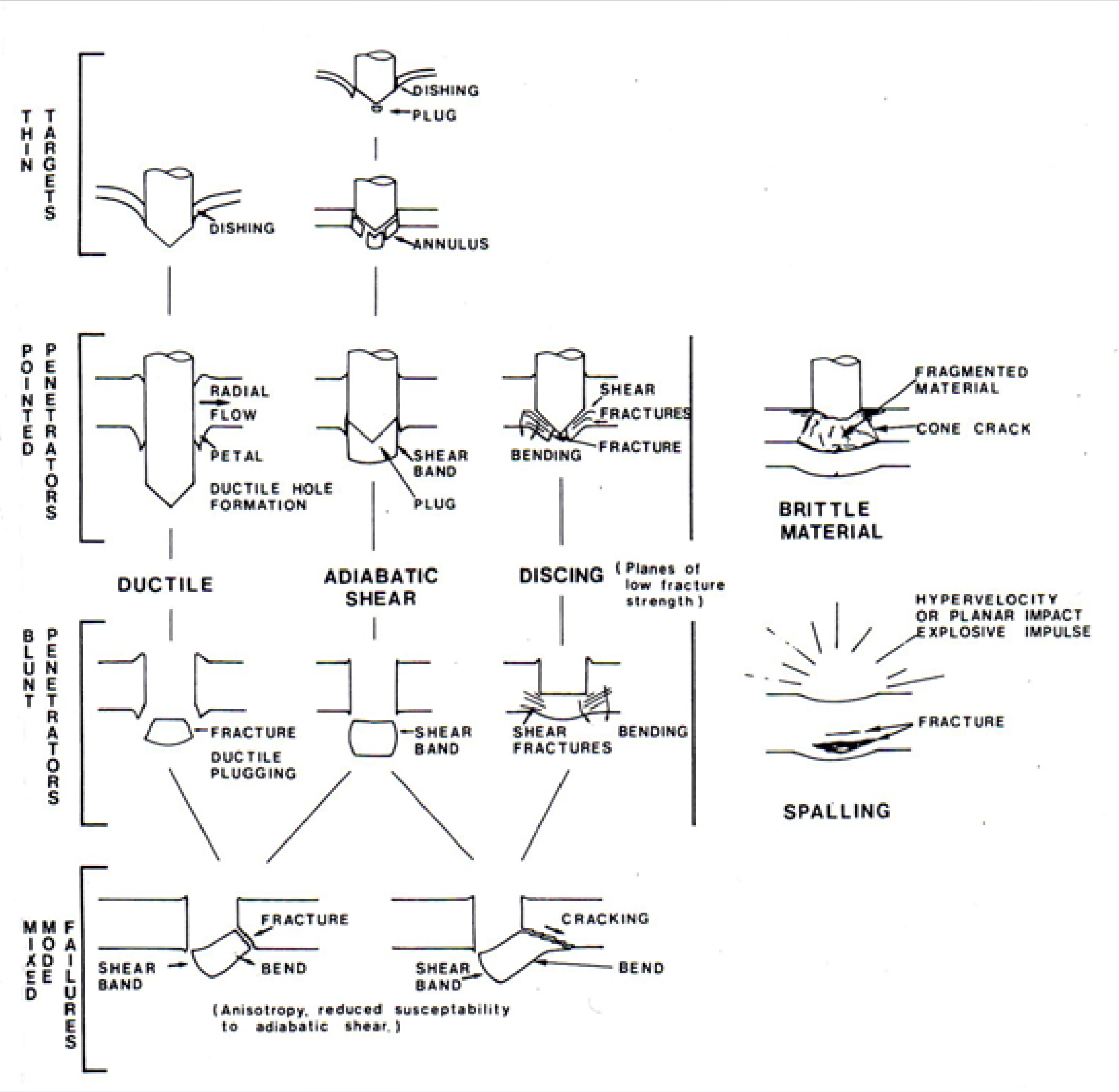


Failure of Materials





Failure of Materials



Classification of failure modes to illustrate the effects of material properties and structure and projectile and plate geometry

Threads of Armoured Vehicles

KE-projectiles bullets

kinetic energy

- bullets not deformable < 800 m/s
  - penetration of rigid body
- deformable long rods > 1000 m/s
  - hydrodyn. penetration
  - depends on strength

Shaped Charges

particle-jet > 5000 m/s

hydrodyn. penetration

depends not on strength

EFP

explosively formed penetrator

deformable penetrator > 2000 m/s

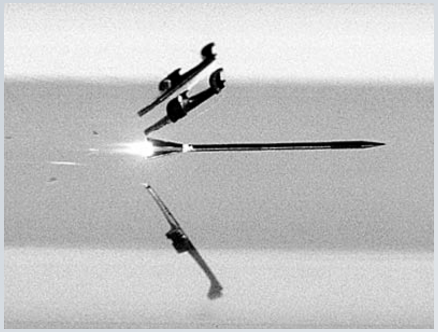
hydrodyn. penetration may be depending on strength

Fragments

kinetic energy

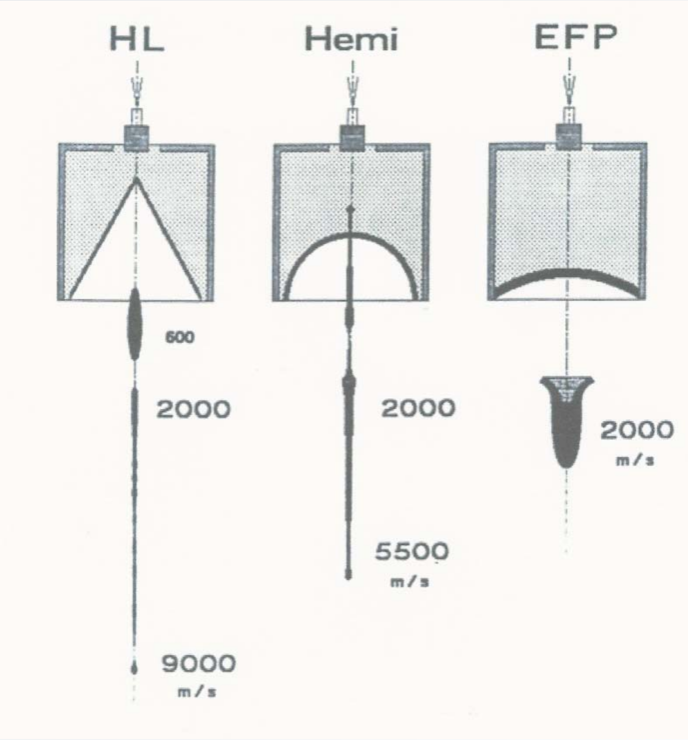
deformable parts > 1000 m/s

hydrodyn. penetration may be depending on strength



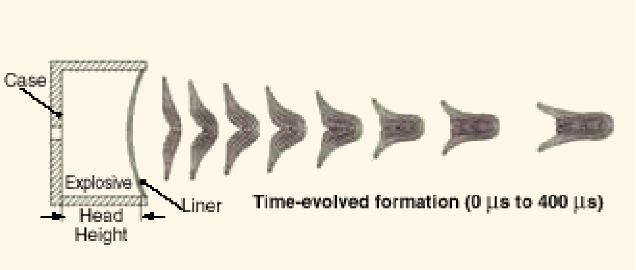
KE-Penetrator

„long rod“

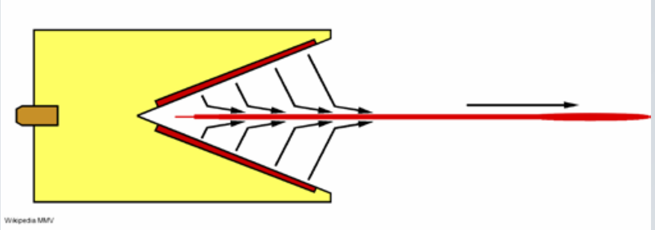


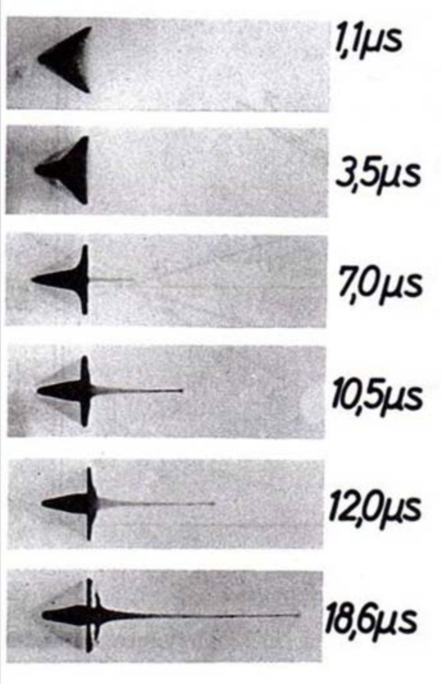
EFP

Homemade EFP



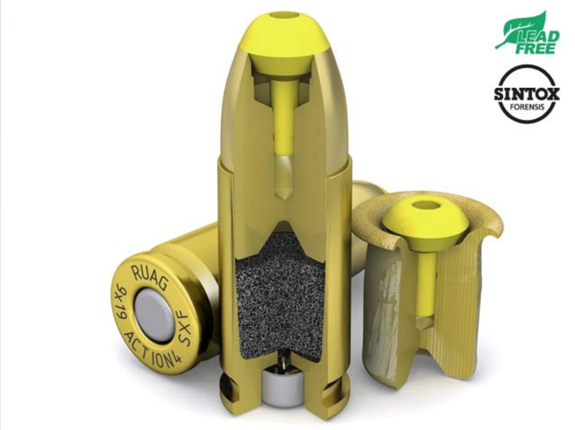
Shaped charge



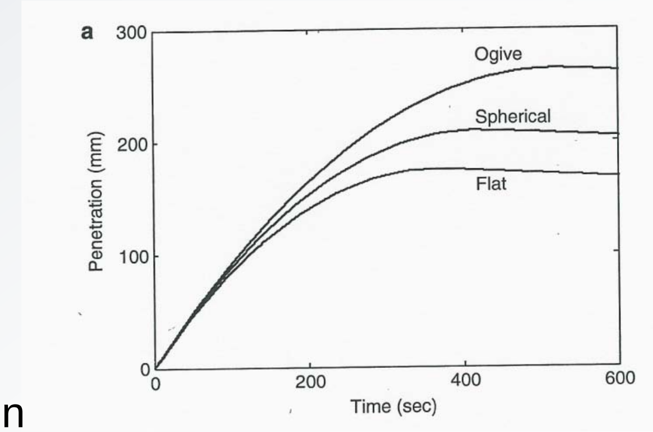


Bullets

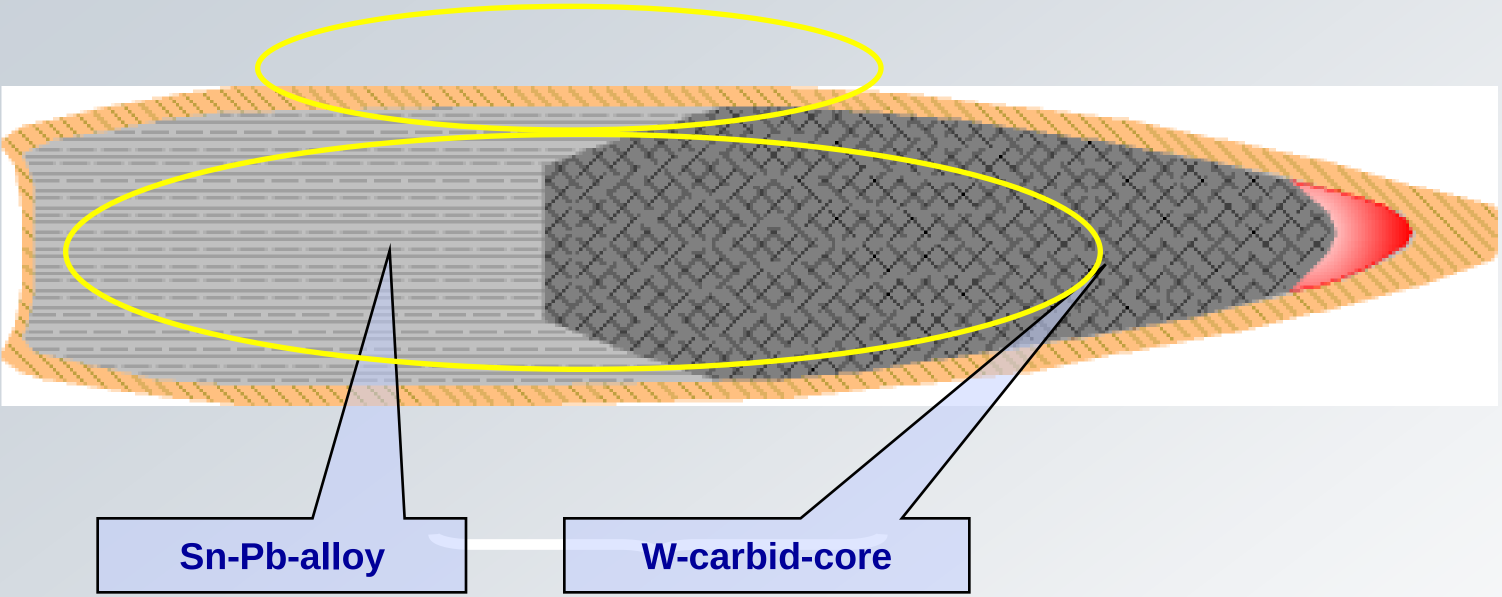
different nose shapes



deformation ammunition: Action



AP Projectiles



Core is consisting mainly of hardened steel (HRc 60 – 64 und ρ = 7,85 g/cm^3)

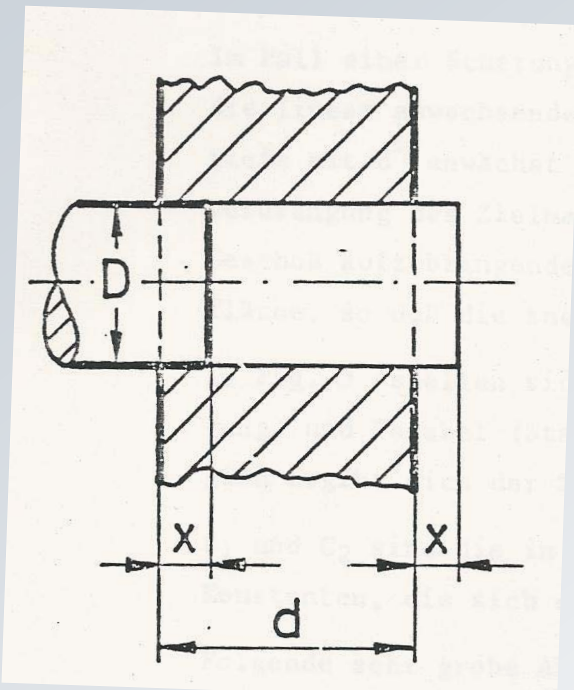
Specially designed models are of WC having an increased hardness and a density ρ = 13,5 – 15 g/cm^3 , L/D-ration of 3:1 bis 5:1

V_p = < 1 km, Machinengun < 1,3 km, Kinetic Energy = 10^3 - 10^4 J

Classical equations of perforation

$$F_{Shear}(x) = (t - x)\, D\, \pi\, \tau$$

F_{Shear} = specific shear resistance,
t = thickness of armour plate,
x = penetration,
D = caliber of bullet,
τ = shear resistance of armour plate



shear plugging

$$E_{Shear} = D\, \pi\, \tau \int_0^t (t - x)\, dx \;=\; D\, \pi\, \tau\, \frac{t^b}{2} \;=\; C_1\, D\, t^b$$

$\tau = 0.5\, \sigma$

$b = 2$

Noble : $b = 2.035$ for 250 mm $\leq$ t $\leq$ 500 mm

$b = 1.654$ for 100 mm $\leq$ t $\leq$ 250 mm

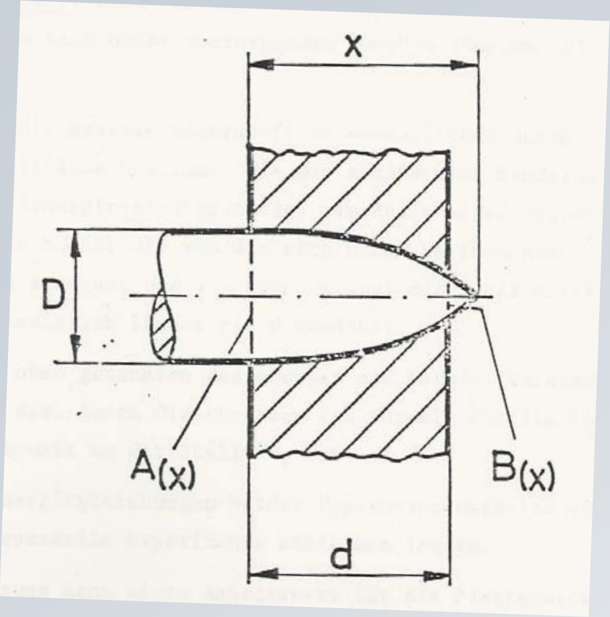
Hélie : $b = 3/4$

C_1 is constant for a specific b

Gâvre : $b = 4/5$

Moisson assumed C_1 depending from impact velocity by

$$\mathbf{C_1 = C' / v}$$



Martel assumed in his theory that for the penetration and perforation of a bullet the energy is proportional to the plastically displaced volume of target material:

$$\mathbf{E_{dis}\ (x) = C\ V\ (x)}$$

displacement of materials

x = penetration, V = displaced volume,
E_{dis} = energy for displace material

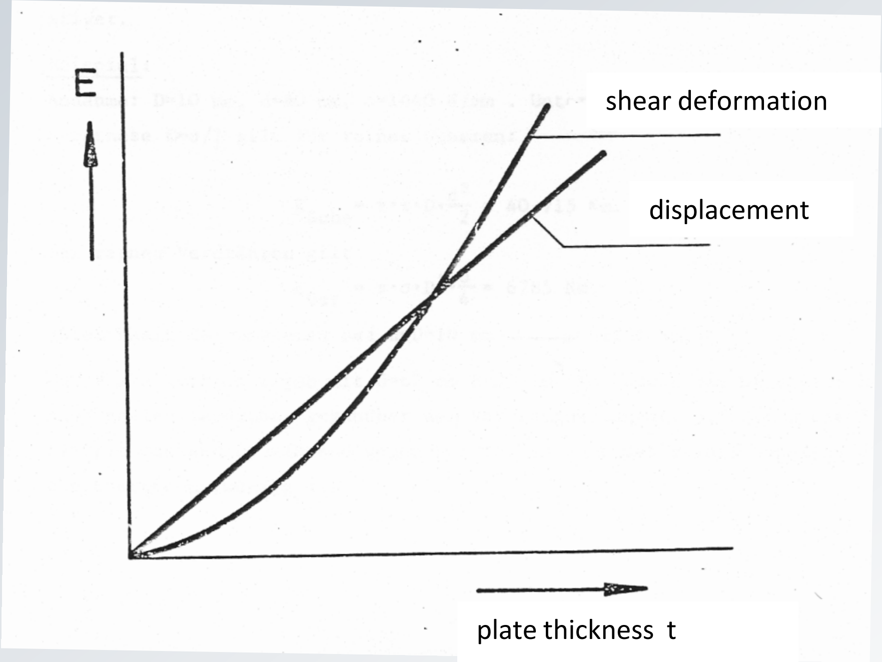
A bullet having a diameter of D will lose the energy E_{dis} during a perforation of an armour plate with a thickness of t

$$E_{dis} = C\,\pi\,\frac{D^2}{4}\ t = C_2\,D^2\,t$$

The resistance against penetration at x is given by a differentiation of E_{dis} to x

$$F_{dis}(x) = dE_{dis}/dx = C\, dV(x) / dx = C\, A(x) \qquad \text{for} \quad x \leq t$$

$$F_{dis}(x) = C[A(x) - B(x)] \qquad \text{for} \quad x > t$$



For thin armour plates shearing is dominating, whereas for thicker plates displacing of target materials dominates the perforation

An acceptable approximation was achieved by a combination of the two equations:

$$E = A\,E_{Shear} + B\,E_{dis} = A\,C_1\,D\,t^2 + B\,C_2\,D^2\,t$$

A + B are factors for distribution

For practical application the two terms were transformed in one term:

$$E = C\,D^a\,t^b$$

$a > 1,\quad b > 1,\quad a + b \approx 3$

C depends on impact velocity, penetration velocity, shape of the bullet and the materials properties of the bullet and armour plates

The two most famous equations of this type are these von Krupp and de Marre:

Krupp: $E = B_1\,D^{5/3}\,t^{4/3}$

de Marre: $E = B_2\,D^{1.5}\,t^{1.4}$

de Marre the sum of the exponents amounts to 2.9

Tate-Theorie for KE-Projectiles

Tate‘s equation is based on Bernoulli-Equation. Tate added materials strength of projectile and target.

$$\tfrac{1}{2}\,\rho_P\,(v_P - u)^2 + Y_P = \tfrac{1}{2}\,\rho_T\,u^2 + R_T$$

ρ_P = density of rod, ρ_T = density of target, v_P = impact velocity, u = penetration velocity,
R_T = dyn. resistance of target, Y_P = dyn. strength of long rod

Dyn. strength of long rod $Y_P = 1.7\ \sigma_P$

Dyn. resistance of the target: $R_T = \sigma_T\ [2/3 + \ln(0.57 + \sigma_T / E_T)]$

σ_P = *flow stress of the long rod*
σ_T = *flow stress of the target*
E_T = *young‘s modulus of target*

Tate A: “A Theory for the Deceleration of Long Rods …”, J. Mech. Phys. Solids, 17, 15, p. 387 ff, 1967

The relative magnitudes of R_T and Y_P influence the penetration principally

Case $R_T < Y_P$

Y_P is larger or equal to the right-hand, rod penetrates like rigid body: $u = V_P$

$$Y_P \geq \tfrac{1}{2} \rho_T u^2 + R_T$$

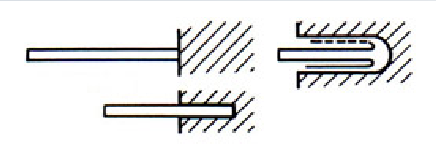
V_P slightly increased compared to u ➔ 70% of long rod

Case $R_T > Y_P$

Penetration occurs if the left-hand becomes larger than R_T

$$\tfrac{1}{2} \rho_P v_P^2 + Y_P \geq R_T$$

➔ 20% of long rod



Target: P900 (HNS)

280HV30, V_p = 1700 m/s

380 HV30, V_p = 1700 m/s

AP Projectiles

Early Research discovered that the perforation of ceramic armor systems occurred in three general stages:

1: shattering
2: erosion
3: catching

During the shattering phase the penetrator fractures and breaks on the surface of the ceramic plate.

This initial stage is followed by a period of damage accumulation in the ceramic material initiated by tensile wave reflections and bending of the ceramic tile and backing plate.

In the final catching phase ceramic and backing combine to reduce the velocity through momentum transfer mechanisms.

The defeat mechanism for hard-core AP projectiles is primarily stages 1 and 3 with projectile fracture upon impact against an armor plate having sufficient hardness and/or high obliquity

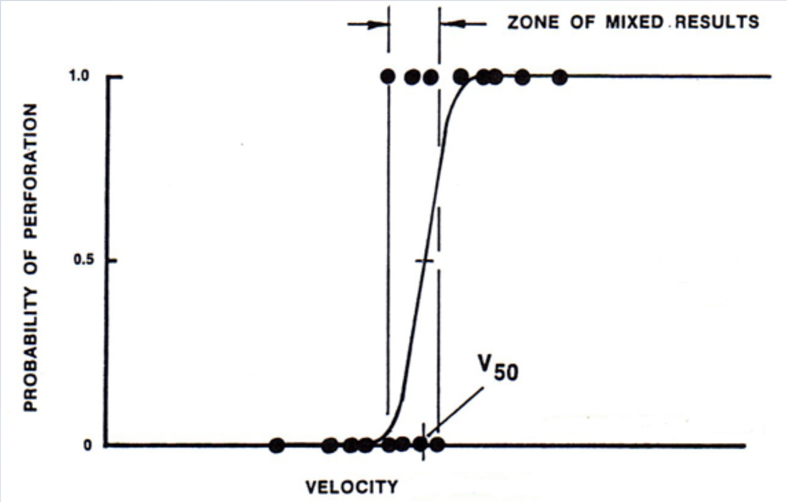
Evaluation of Ballistic Performance

Balistic Limit (V_{50})

The **ballistic limit** or **limit velocity** is the velocity required for a particular projectile to reliably (at least 50% of the time) penetrate a particular piece of material. In other words, a given projectile will not pierce a given target when the projectile velocity is lower than the ballistic limit [1]. The term *ballistic limit* is used specifically in the context of armour

[1] **D. E. Carlucci, S. S. Jacobson, *Ballistics: Theory and Design of Guns and Ammunition, CRC Press, 2008, p. 310***

The ballistic limit for small-caliber into homogeneous armour is:



$$V_{50} = 19.72 \left[\frac{7800\, d^3 \left[(e_h / d) \sec \theta\right]^{1.6}}{W_T} \right]^{0.5}$$

V_{50} = ballistic limit (velocity)

d = caliber projectile [inch]

e_h = thickness armour [inch]

θ= obliquity

W_T = mass of target [lbs]

Evaluation of Ballistic Performance

Equation of Lambert and Jonas:

$$\mathbf{V_R} = \begin{cases} \mathbf{0.0 \leq V_I \leq V_L} \\ \boldsymbol{\alpha (V_I^k - V_L^k)^{1/k}, \; V_I > V_L} \end{cases}$$

$$\tfrac{1}{2} m_{\mathbf{P}} V_{\mathbf{I}}^{\mathbf{2}} = \tfrac{1}{2}(m_{\mathbf{Res}} + m_{\mathbf{plug}}) V_{\mathbf{Res}}^{\mathbf{2}} + E_{\mathbf{plug}} = \tfrac{1}{2}(m_{\mathbf{Res}} + m_{\mathbf{plug}}) V_{\mathbf{Res}}^{\mathbf{2}} + \tfrac{1}{2} m_{\mathbf{P}} V_{\mathbf{50}}^{\mathbf{2}}$$

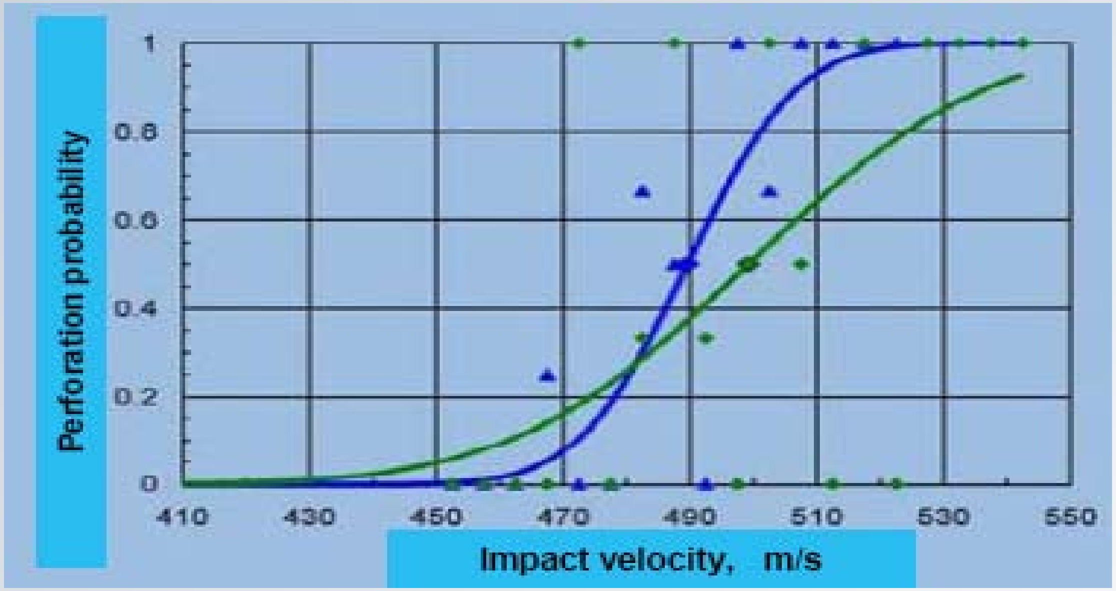
$\mathbf{E_{plug}}$ = Energy for plugging

Assumption: same velocity for plug and residual projectile

➔ in reality often not fulfilled

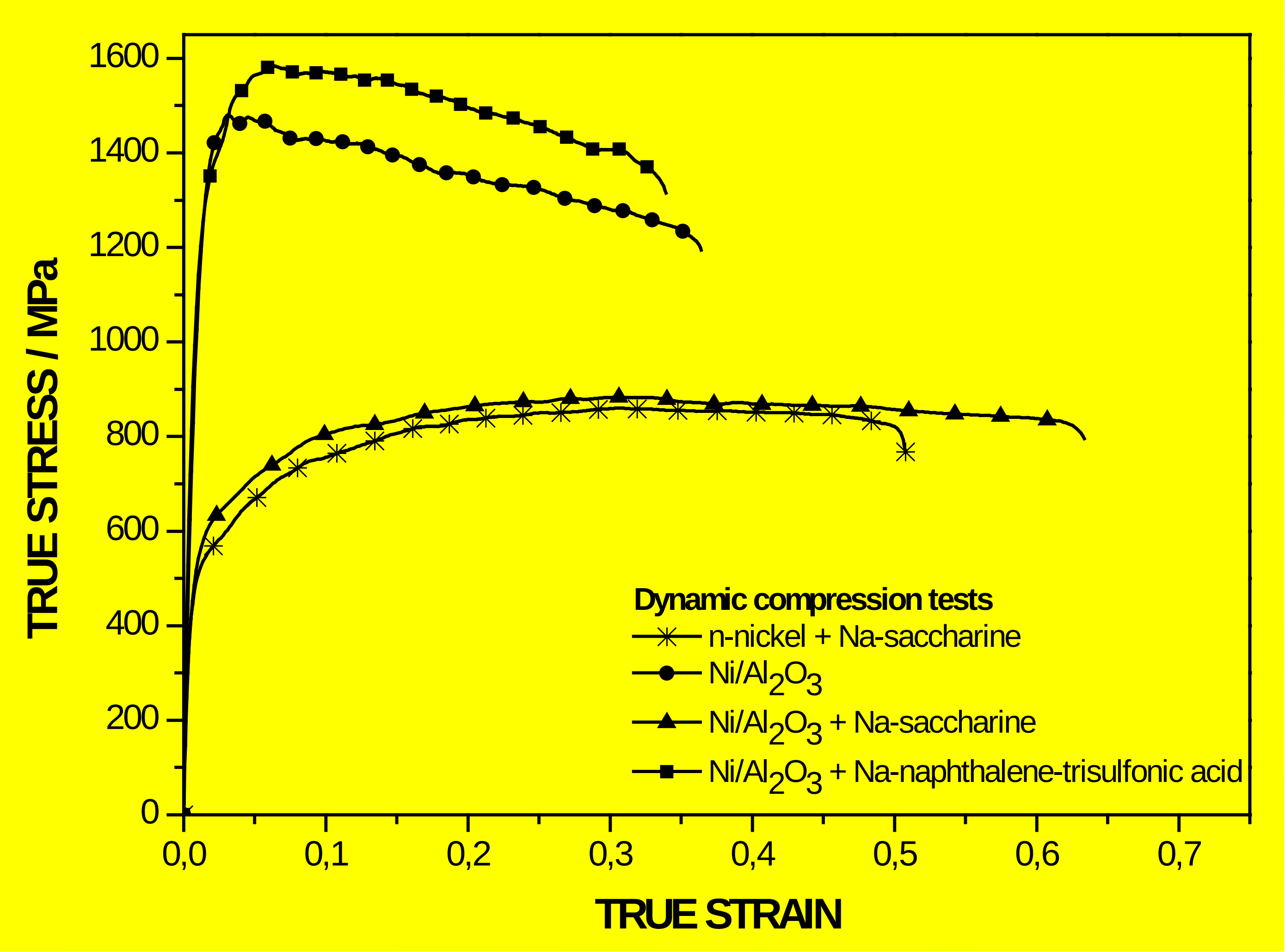
But: good approximation with k = 2 and determination of α by regression

Heterogeneous Material

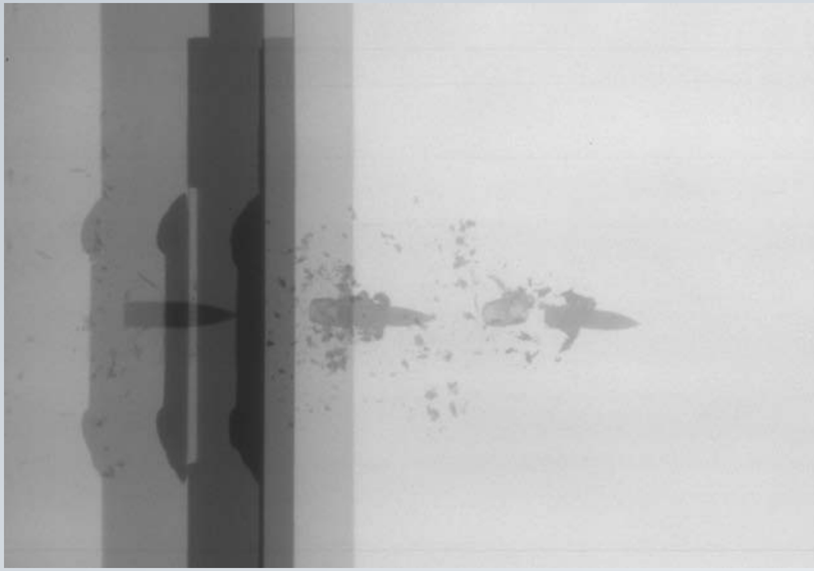


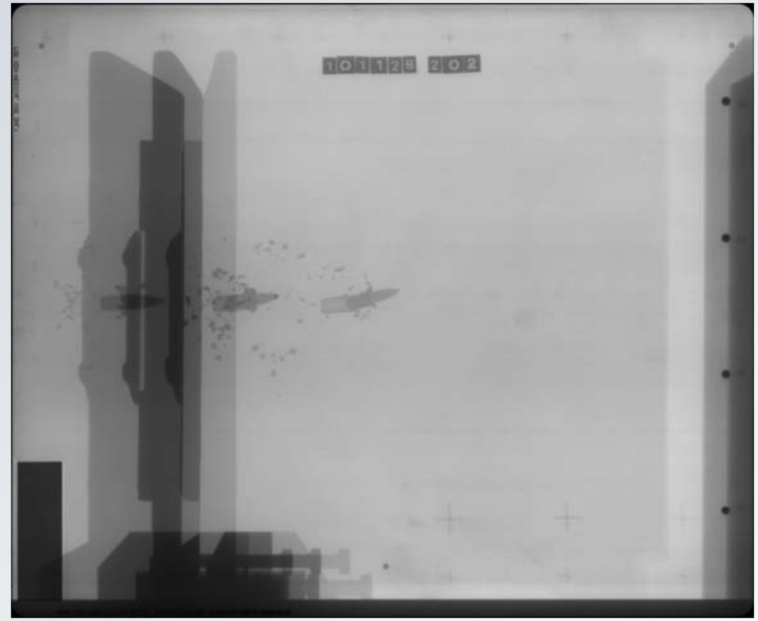
Homogeneous armour materials based on metals and ceramics may adequate tested by the V_{50} method with < 14 shots. For heterogeneous materials like fibre reinforced composites more shots (<30) are necessary. The standard deviation should be taken also in consideration.

Nano-Composite (nano-Ni + nano-Al_2O_3)



WC-bullet / nano-Composite





v_I [m/s]	v_R [m/s]	Phi [°]
837	790	0.2
836	788	3.2

Plate: nano Ni reinforced with nano Al_2O_3

thickness = 5 mm

➔ effect on the bullet is negligible

APDSFS (armor-piercing, discarding-sabot, fin stabilized)

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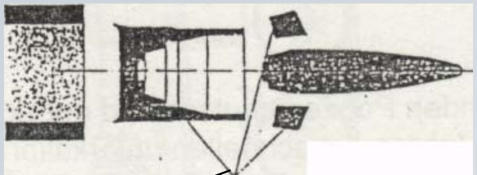
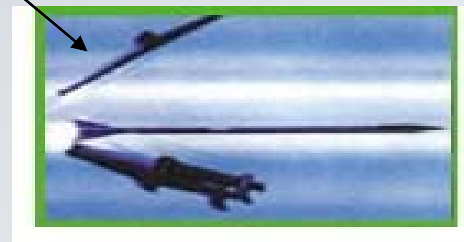
Sabot



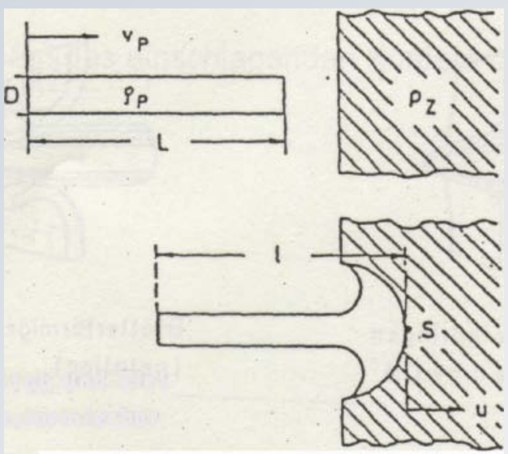


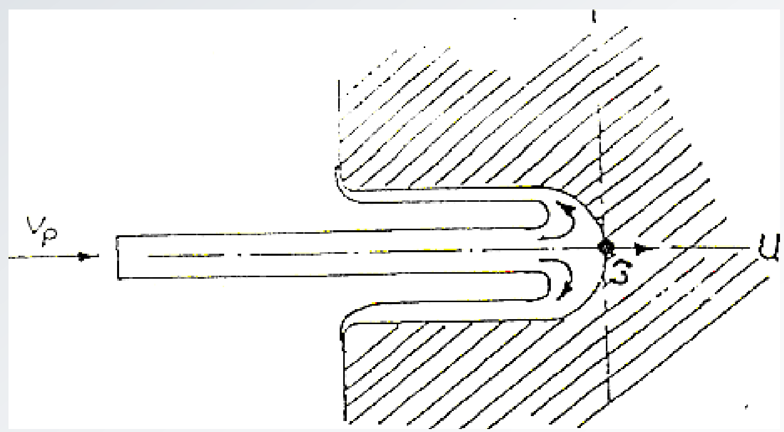
Sabot

L/D << 4:1

L/D up to > 30:1

Carl Cranz: $P \sim \rho \cdot D \cdot L/D \cdot V_P^2$





Hydrodynamic Penetration

Long Rod Penetration (KE)

The defeat of long rod penetrator (LRP) is more complex than for conventional AP projectiles.

Penetrators are made of high strength, high density materials, such as W sintered alloy or depleted U, having densities near 18 g/cm^3 and moderate hardness, good toughness and ductility.

They are not susceptible to shattering like brittle AP projectiles.

Caliber from 20 mm up to > 140 mm.

High L/D ratio (exceed 30 : 1), Velocity 1.3 - >1.6 km/s.

Yields kinetic energy in excess of 10^6 J.

Creating high energy density per unit area of a target impacted.

The primary defeat mechanism is erosion.

Classification of Impact Processes *(high L/D)*

I: $P_H = \rho\, u_s\, u_p$

time ~ 1 ns

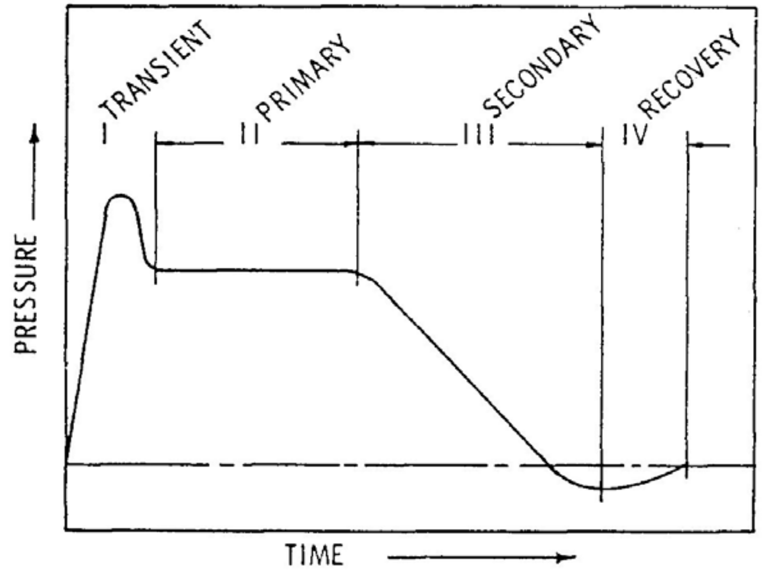
one-dimensional stress state

II: steady-state

fluid flow- like

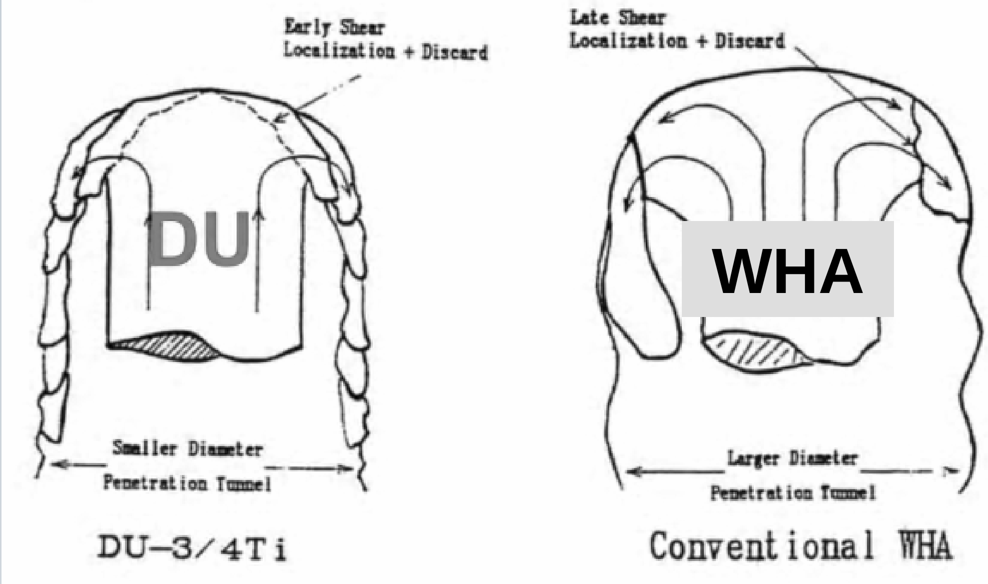
erosion of rod

$P > \frac{1}{2} \rho\, u_p^2$



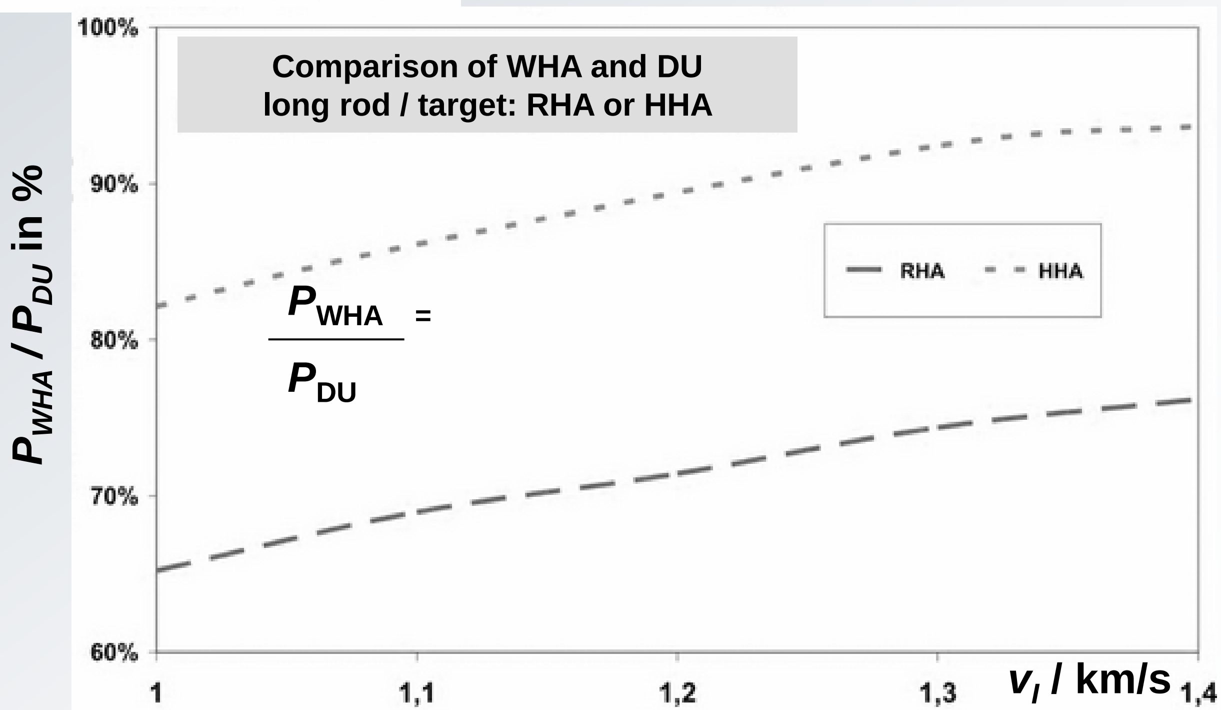
III: cavitation stage, after erosion, expansion of crater ↔ trapped energy

IV: small stress level, no gross plastic deformation, several target reactions: brittle spalling, recristallisation



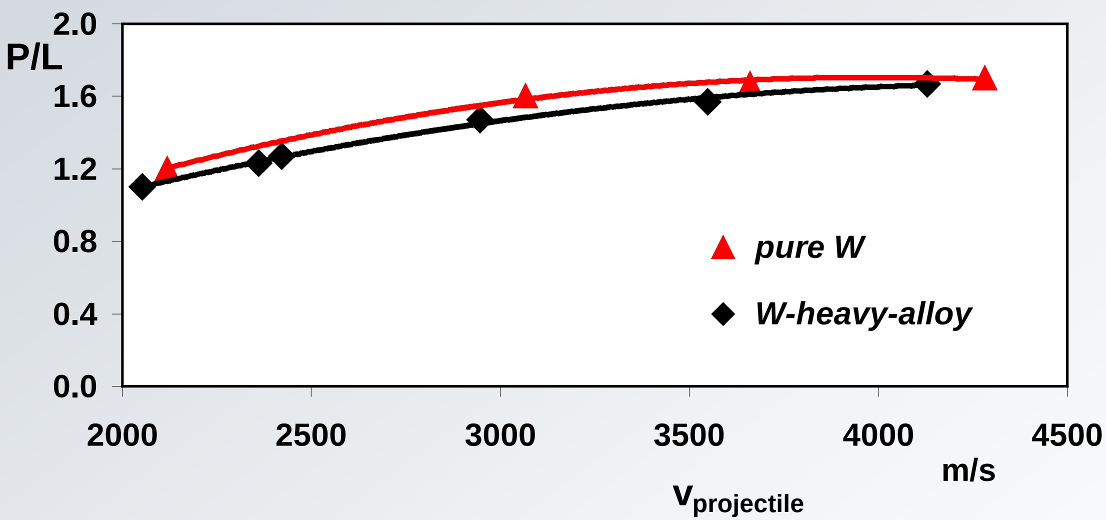
1. DU-crater narrower,
but 5 % - 35 % deeper

inceasing V_l and increasing hardness of target material decreasing the difference between DU and WHA.



Stein W, Fa Rheinmetall; Magness L, US-ARL; EMI; ISL; Internet; 23rd Int. Symp on Ballistics

Crater shapes due to rod impact



Pure W does not form adiabatic shear bands
➔ different shape of crater

DoP *(Depth of Penetration)*

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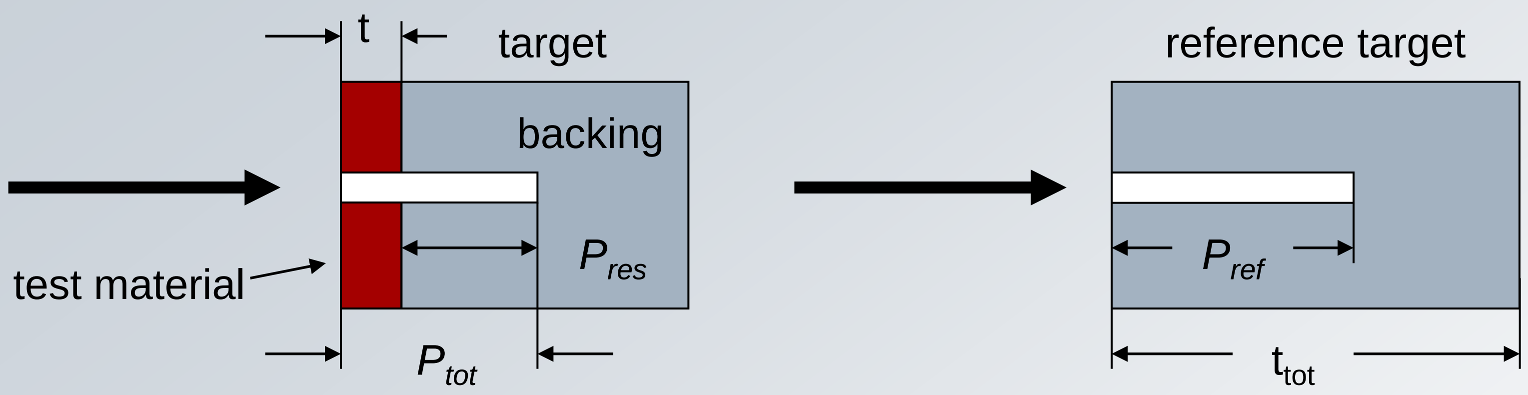


effectiveness factor

equivalence factor

Volume

$$E_s = \frac{P_{ref}}{P_{tot}}$$

$$F_s = \frac{t_{ref}}{t}$$

$$t_{ref} = P_{ref} - P_{res}$$

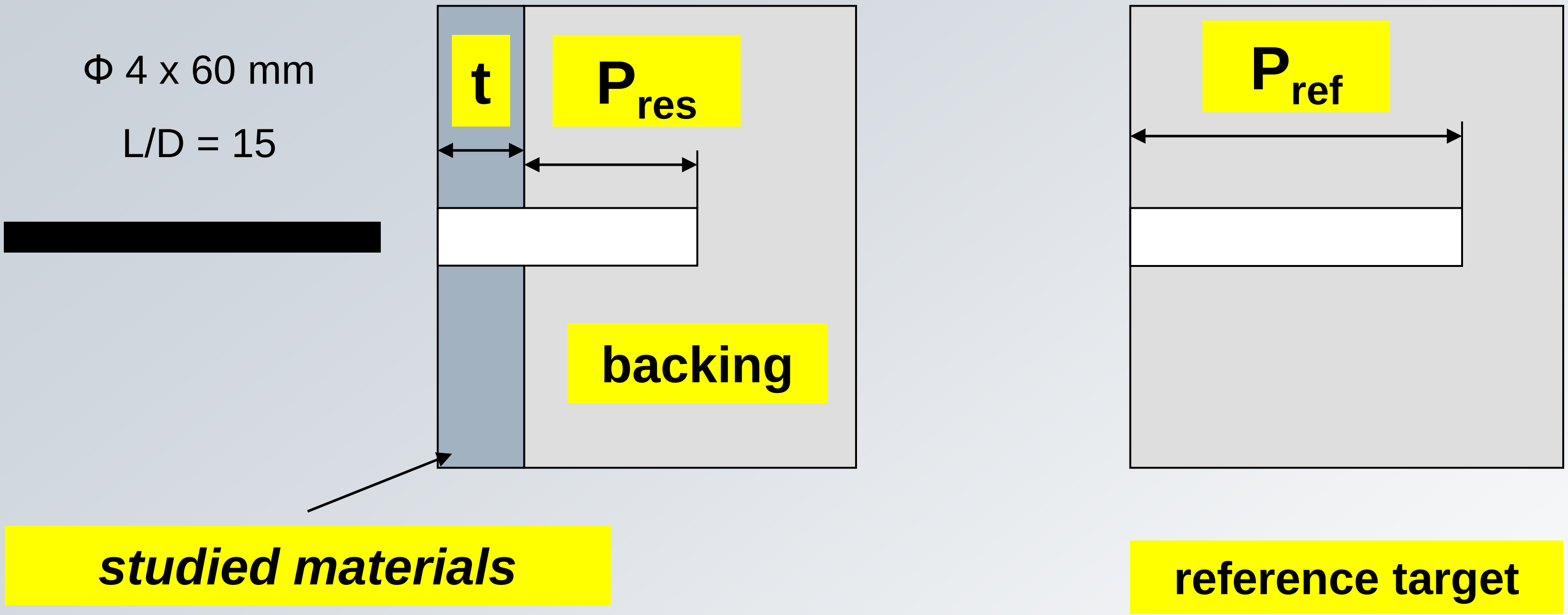
Mass

$$E_m = E_s \frac{\rho_{ref}}{\rho_{tot}}$$

$$F_m = F_s \frac{\rho_{ref}}{\rho}$$

equivalence factor = evaluation of test material only
effectiveness factor = evaluation of both test material and backing

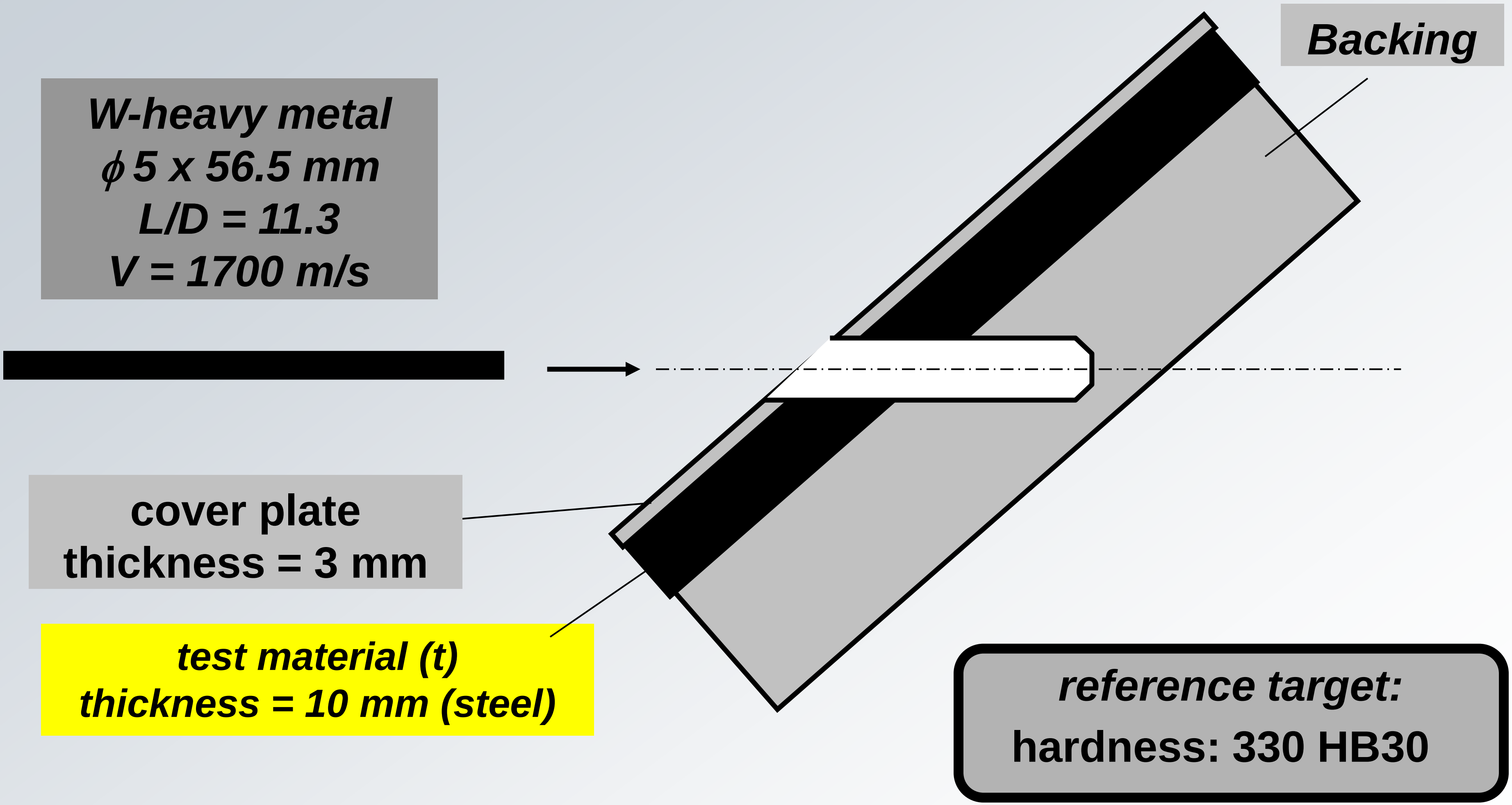
Target NATO 0° (test configuration)



$$F_m = (P_{ref} - P_{res}) / t \cdot \rho_{ref} / \rho$$

$$E_m = (P_{ref} \cdot \rho_{ref}) / (t\,\rho + P_{res}\,\rho_{res})$$

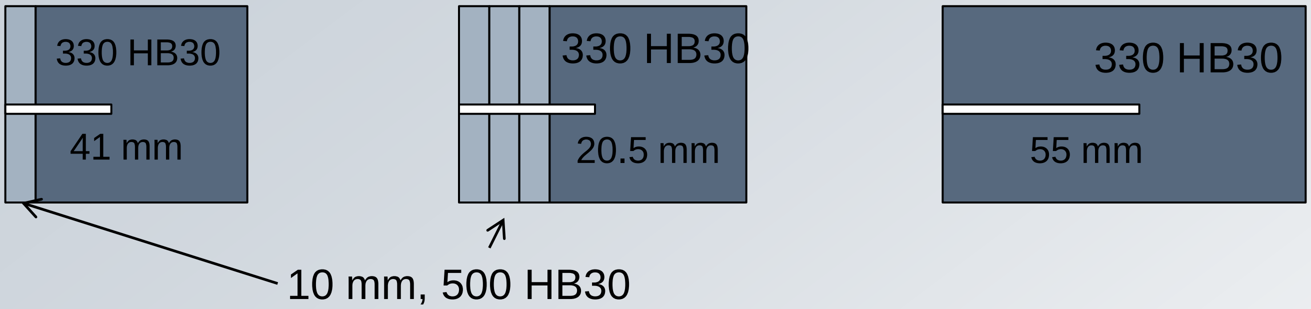
Target NATO 60° (test configuration)



Target NATO 60°

$$F_m^{60°} = \frac{P_{ref} - (\text{cover plate} + P_{res})}{t} \times \frac{\rho_{ref}}{\rho}$$

used to evaluate the results



$F_m = (P_{ref} – P_{res}) / t$

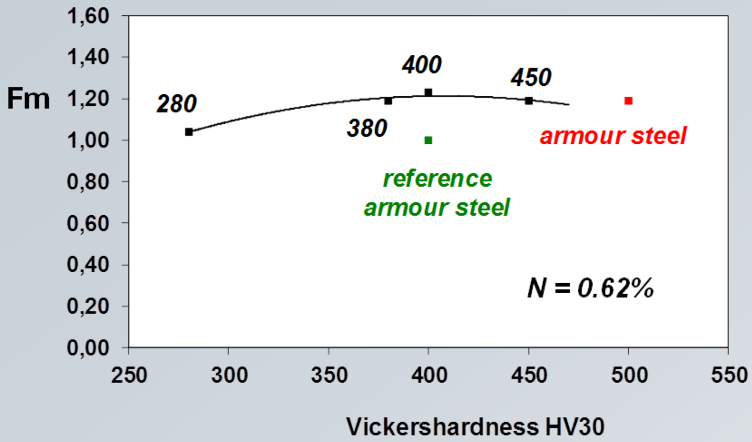
$E_m = P_{ref} / (t + P_{res})$

$F_m = 1.4$
$E_m = 1.09$

$F_m = 1.15$
$E_m = 1.08$

➔ Fm values are depending on thickness of studied materials

➔ Em values: crater length of studied materials and backing is added and leads to different results. This is becoming important if backing and studied material are of different density



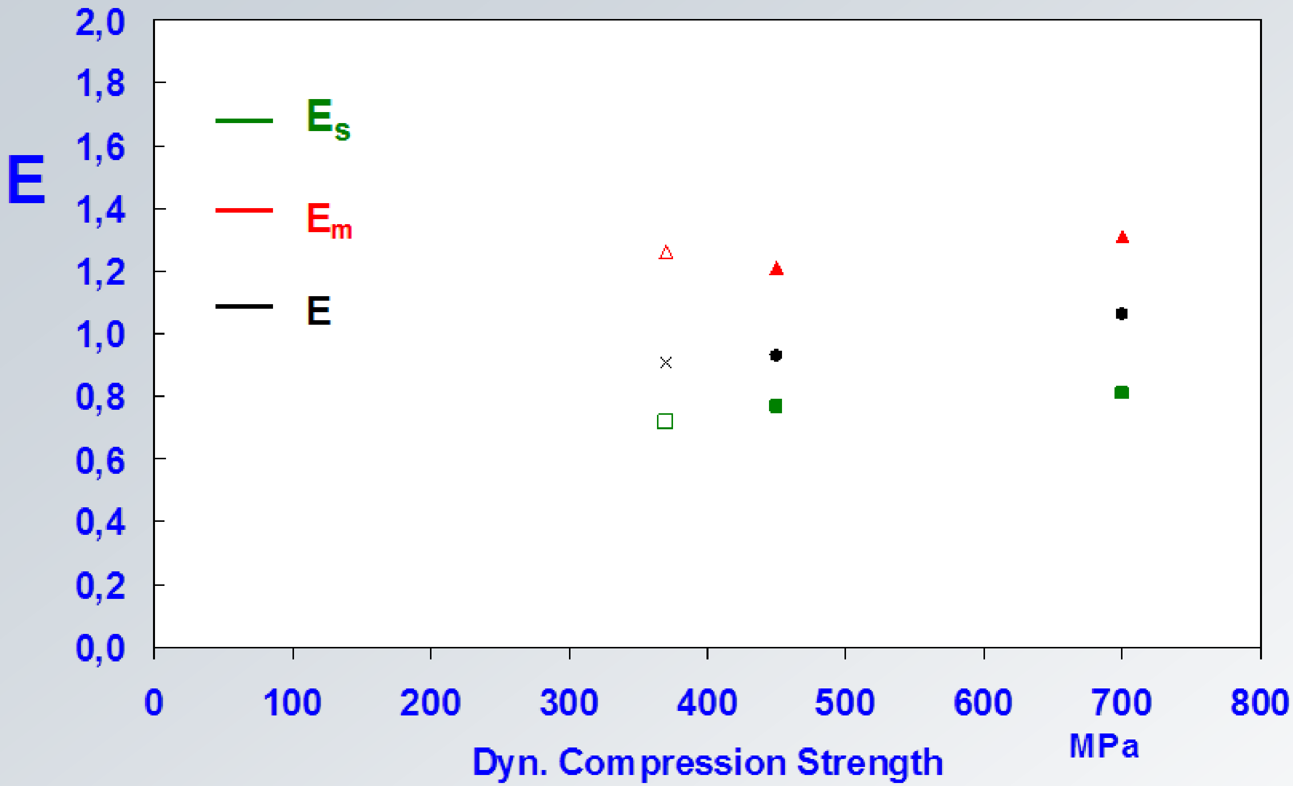
Different treated P900 (HNS), increasing hardness increases susceptibility to ASB
➔ protection capability decreases

280HV30

400HV30

450HV30

CFC Material



CFC materials

E_s values have to take in consideration for materials with low density