MINIMUM IMPACT ENERGY FOR KE-PENETRATORS IN RHA-TARGETS

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Abstract : The Odermatt formula presented originally in 1992 [3] also allows to determine minimum energy impact velocities for penetrating inclined RHA plates. For plates of 800 MPa ultimate tensile strength (UTS) this velocity is around 1900 m/s.
However this velocity may considerably be reduced by tailoring the sabots for specific rods, taking into account rod length, barrel caliber and maximum acceleration. Then the optimum velocity value drops to about 1700 m/s. To compensate the velocity drop at tactical range (typically 2000 m) about 80 m/s increase has to be considered.
On the other hand the influence of the muzzle velocity dependent efficiency of solid propellant gun systems downshifts the optimum velocity to about 1540 m/s for 2000 m range.
Jacketed penetrators and sabots using new high strength light materials (e.g. FRP), allow to reach the required penetration at even lower energy levels.

1. PENETRATION LIMIT FORMULA

1.1 Penetration limit definition

In a finite target penetration limit means that the projectile reaches the rear face of the target and spalling opens the penetration channel. The penetrator residue will have a length of one to one and a half diameters. In a few of our experiments the residue stuck in the exit crater or dropped to the floor in the immediate vicinity of the target. This result is observable at the target site, whereas a semi-infinite target first has to be cut up laboriously.
The formula described below allows a quick estimation of the target inclination necessary for a penetration limit. This is then easily established with few projectiles, especially when using witness plates.

1.2 Governing parameters

D	penetrator diameter [mm]	λ, λ_W	aspect ratio L/D, L_W/D
L	overall tungsten penetrator length [mm]	v_T	impact velocity [km/s]
L_W	working length of penetrator [m]	v_0	muzzle velocity [m/s]
ρ_P	penetrator density [kg/m^3]	θ	angle of obliquity
ρ_T	target density [kg/m^3]	m_P	penetrator mass [kg]
d	target plate thickness [mm]	m_G	mass of penetr. and sabot [kg]
UTS	target material ultimate tensile strength [MPa]	m_L	propellant charge mass [kg]
P	penetration channel length [mm]	E_P	impact energy [MJ]

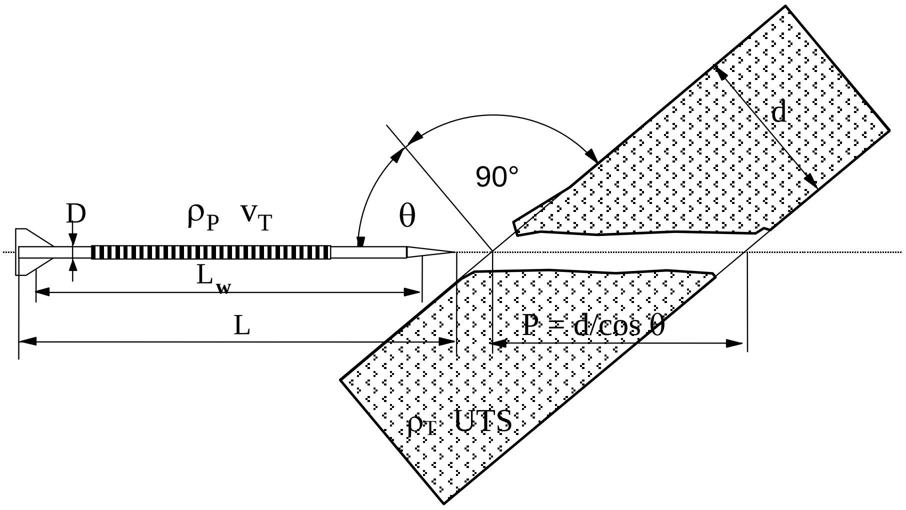

Figure 1: Definition illustration

1.3 Penetration limit formula

The formula has been published in [3] and [4]. Here it is presented with a slight variation, ie. P/L as the independent variable instead of d/D.

$$\frac{P}{L_w} = \underbrace{f(\lambda_w)}_{A} \cdot \underbrace{\cos^m \theta}_{B} \cdot \underbrace{\sqrt{\frac{\rho_P}{\rho_T}}}_{C} \cdot \underbrace{e^{\frac{-c \cdot UTS}{\rho_P \cdot v_T^2}}}_{D} \qquad (1)$$

A aspect ratio influence,
a good approximation is obtained with the following equation

$$f(\lambda_W) = 1 + a_1 \cdot \frac{1}{\lambda_W} \cdot \left(1 - \tanh \frac{\lambda_W - 10}{a_2}\right) \quad \text{mit} \;\; a_1 = 3.94 \qquad a_2 = 11.2 \qquad (2)$$

B target inclination influence,
the best fit for the exponent is m = -.225

C penetrator/target density influence, this is the wellknown root ρ-law

D the dimensionless exponent is derived in [1] by applying the π-theorem,
the coefficient c depends on target material strength

$$c = 22.1 + 1.274 \cdot 10^{-2} \cdot UTS - 9.47 \cdot 10^{-6} \cdot (UTS)^2 \qquad (3)$$

1.4 Range of validity of the formula/results

The range of validity is defined by the bandwidth of 74 experiments with 19 different penetrators and calibers of 25 to 140 mm.

penetrators:				
L	90	-	950	mm
D	8	-	32	mm
λ	11	-	37.5	
m_P	0.1	-	9	kg
ρ_P	17’000	-	17’750	kg/m^3
v_T	1’100	-	2’000	m/s

targets:				
d	40	-	500	mm
UTS	800	-	1’600	MPa
ρ_T			7’850	kg/m^3
θ	0	-	74	°

Since the formula is also based on theoretical analyses extrapolations are permissible, yielding results with only slightly reduced accuracy. This was confirmed by several experiments.

2. APPLICATIONS

2.1 Scope

The above formula allows the comparison of results from firing tests with different target inclinations/thicknesses/material properties, penetrator geometries and impact velocities.
It also allows the evaluation of influences of penetrator aspect ratio, obliquity and other parameters.
Penetrator performance is predictable.
Reliable extrapolations from a single test result are possible.

2.2 Optimisations

The analytical solution permits optimisations. E.g. the **optimum impact velocity** (maximum penetration limit for a given energy) exclusively depends on target strength and penetrator density:

$$v_{opt} = \sqrt{\frac{3\cdot c\cdot UTS}{\rho_P}} \qquad (4)$$

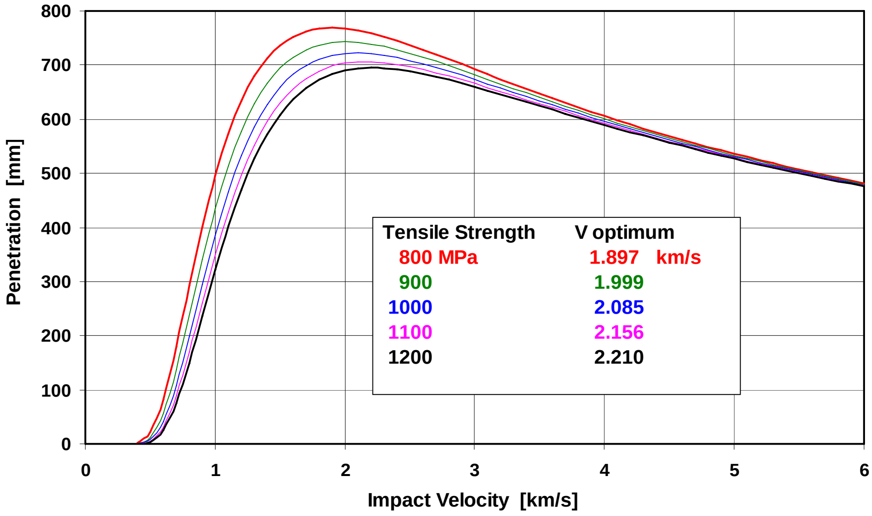

Figure 2: Optimum velocity for 10 MJ constant impact energy

For a given penetration the **optimum penetrator length** is

$$L_{opt} = e^{\frac{1}{3}} \cdot \frac{P}{f(\lambda) \cdot \cos^m \theta \cdot \sqrt{\frac{\rho_P}{\rho_T}}} \qquad (5)$$

It is independent of target UTS. High penetrator aspect ratios require notably less energy. For a penetration limit of 1000 mm an aspect ratio of 30 only needs 27 % of the energy an aspect ratio of 10 requires.

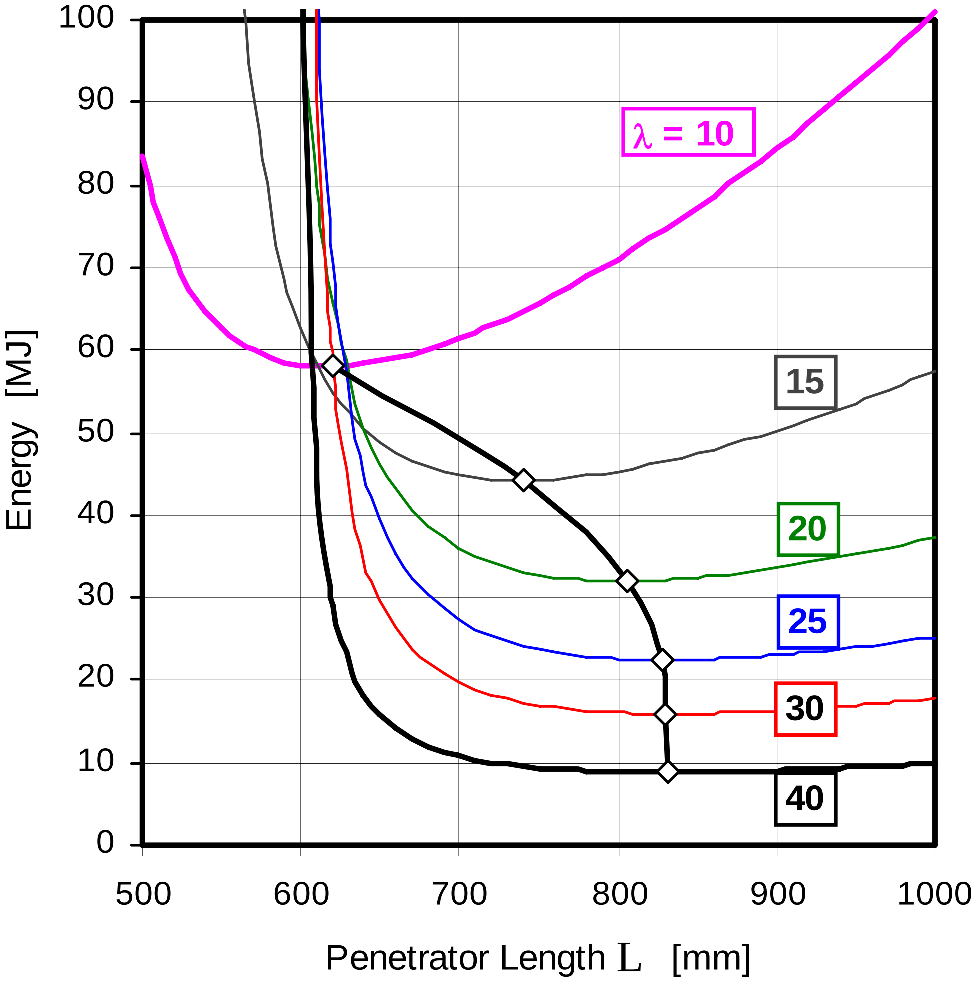

Figure 3: Optimum penetrator length vs. aspect ratio for P = 1000 mm
obliquity 60° / UTS 800 MPa / penetrator density 17500 kg/m^3

It has to be noted that this optimum is purely theoretic, because neither the influence of the sabot nor the influence of the interior ballistics are considered.

2.3 Penetrator layouts

The graph below shows the projectile parameters for a future caliber > 120 mm with penetrator lengths between 750 and 2000 mm and diameters of 22 to 30 mm. This is a specific evaluation referring to a penetration limit of 1000 mm, 60° obliquity, 800 MPa UTS and penetrator density of 17500 kg/m^3.

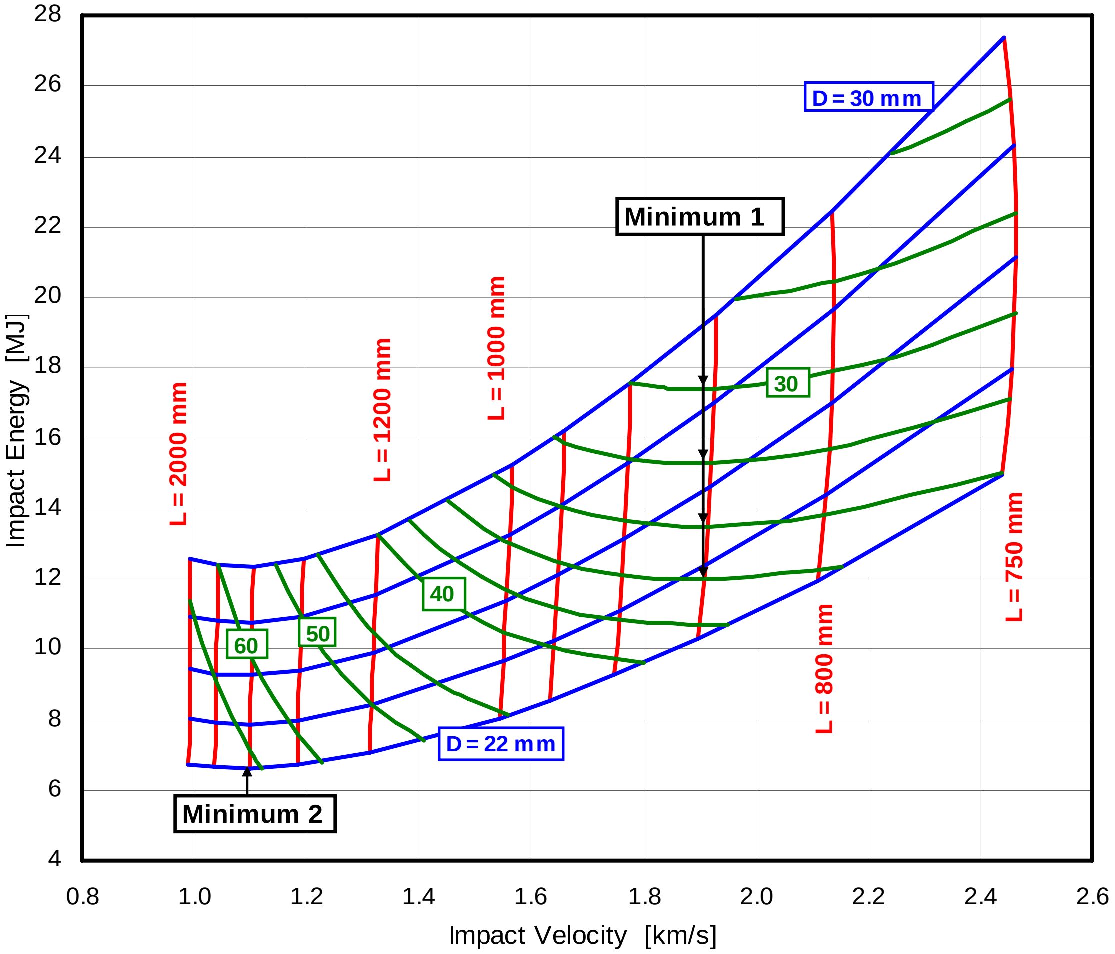

Figure 4: Penetrator parameters for 1000 mm penetration limit

This graph confirms again the fact established by eq. 4 that for a given aspect ratio there exists an optimum velocity, in this case 1897 m/s. This optimum value is often cited by the experts. However this value is not necessarily an optimum.

As shown an increased aspect ratio requires less energy, eq. 4 transforms to

$$v_{opt_2} = \sqrt{\frac{c \cdot UTS}{\rho_P}} \qquad (6)$$

For the above evaluation eq. 6 yields 1095 m/s. This value is not realistic, since a rod of 24 diameter would need a length of 1600 mm. The corresponding aspect ratio of 67 is far from practicable. Fig. 4 graphically shows that for an optimisation velocity is not the only governing parameter.

3. APPLICATION OF THE ODERMATT FORMULA IN A SYSTEM LAYOUT

3.1 Length and aspect ratio (L, λ) of minimum energy KE rods for a required penetration

This is a graphic optimisation as described in item 2.3.
The Odermatt formula yields the penetration limits P for different projectile lengths L vs. projectile impact velocity v_T. These curves are plotted in fig. 5.
An infinite number of L/v_T combinations may be found which attain a required penetration, e.g. P = 1000 mm in 800 MPa UTS RHA at 60° obliquity.
The aspect ratio (λ) influence practically disappears at values above 30. However for an assumed λ (say 36) the projectile mass m_P, the impact velocity v_T and the impact energy E_T are determined. According to the data given in fig. 7 these values are

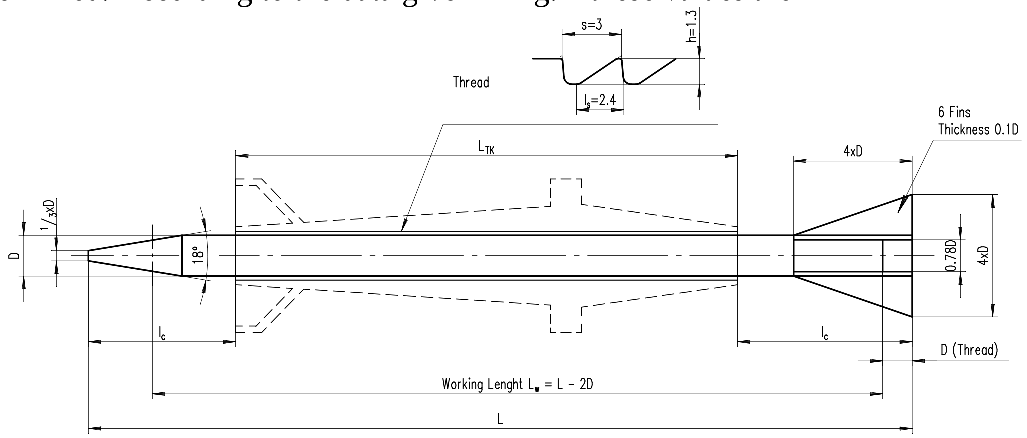

Figure 7: Proportions of tungsten penetrators with titanium fins

L	(mm)	1127	1042	977	926	885	852	825	802	783
v_T	(m/s)	1400	1500	1600	1700	1800	1900	2000	2100	2200
m_P	(kg)	15.24	12.06	9,95	8.48	7.42	6.63	6.02	5.53	5.15
E_P	(MJ)	14.94	13.56	12.74	12.26	12.02	11.96	12.03	12.20	12.46

These results are plotted in fig. 6.
The analytically calculated minimum energy is confirmed at v_T = 1900 with E_P = 12 MJ. It has to be noted that this minimum is not very pronounced: in the region of 1700 to 2100 m/s the energy variation is not more than 2.5 % or below 150 kJ respectively.

3.2 Sabot design influence

The 140 mm caliber with a peak pressure of 750 MPa (7.5 kbar) is taken as a reference for investigating sabot design influence. The maximum acceleration determines sabot dimensions. Fig. 8 shows a conventional aluminium sabot design.

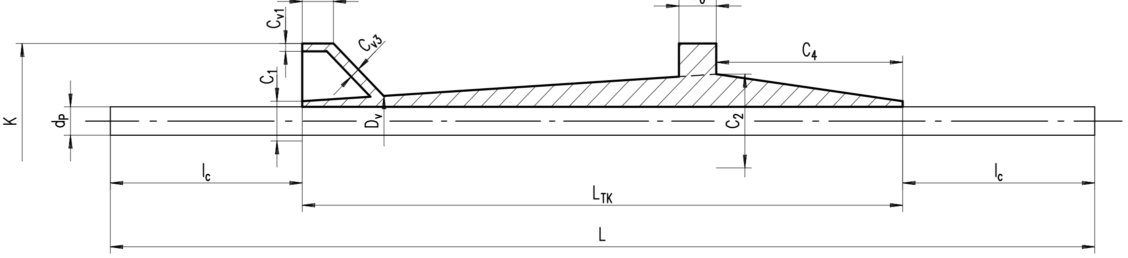

Figure 8: Sabot proportions

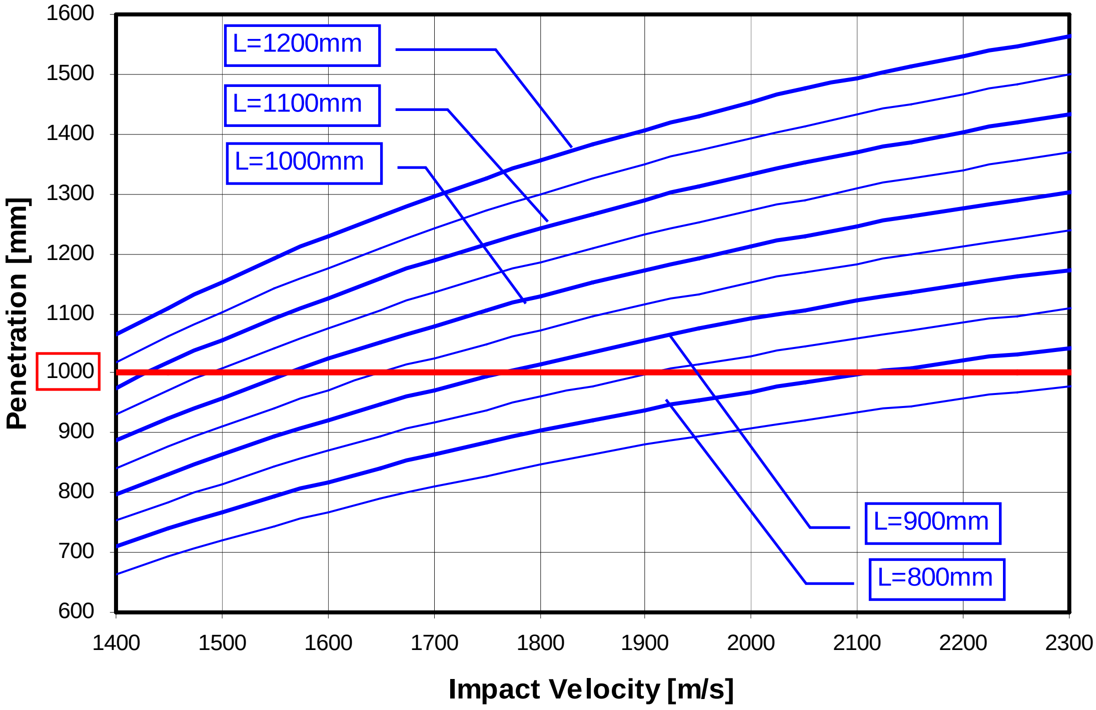

Figure 5 : Penetration limit P vs impact velocity in RHA (800 N/mm^2 UTS / 60° obliquity) in function of length L

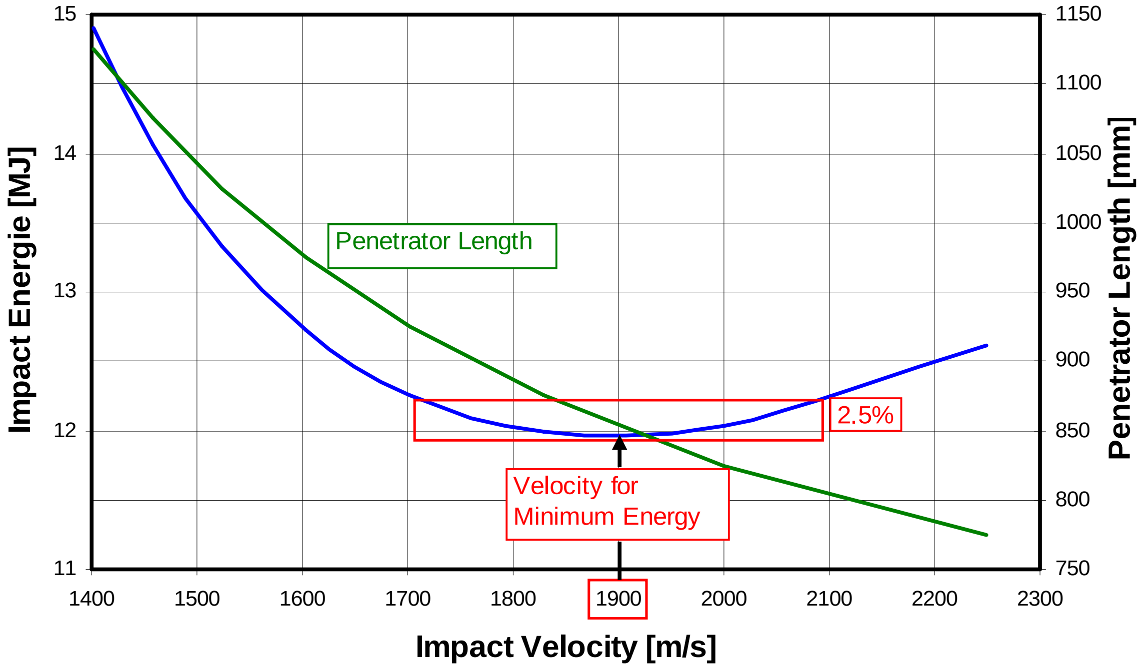

Figure 6 : Penetrators with L/D = 36 with penetration limit of 1000 RHA (800 N/mm^2 UTS / 60° obliquity)

For the penetrators mentioned above sabots were individually tailored, their energies E_S are shown in fig. 9.

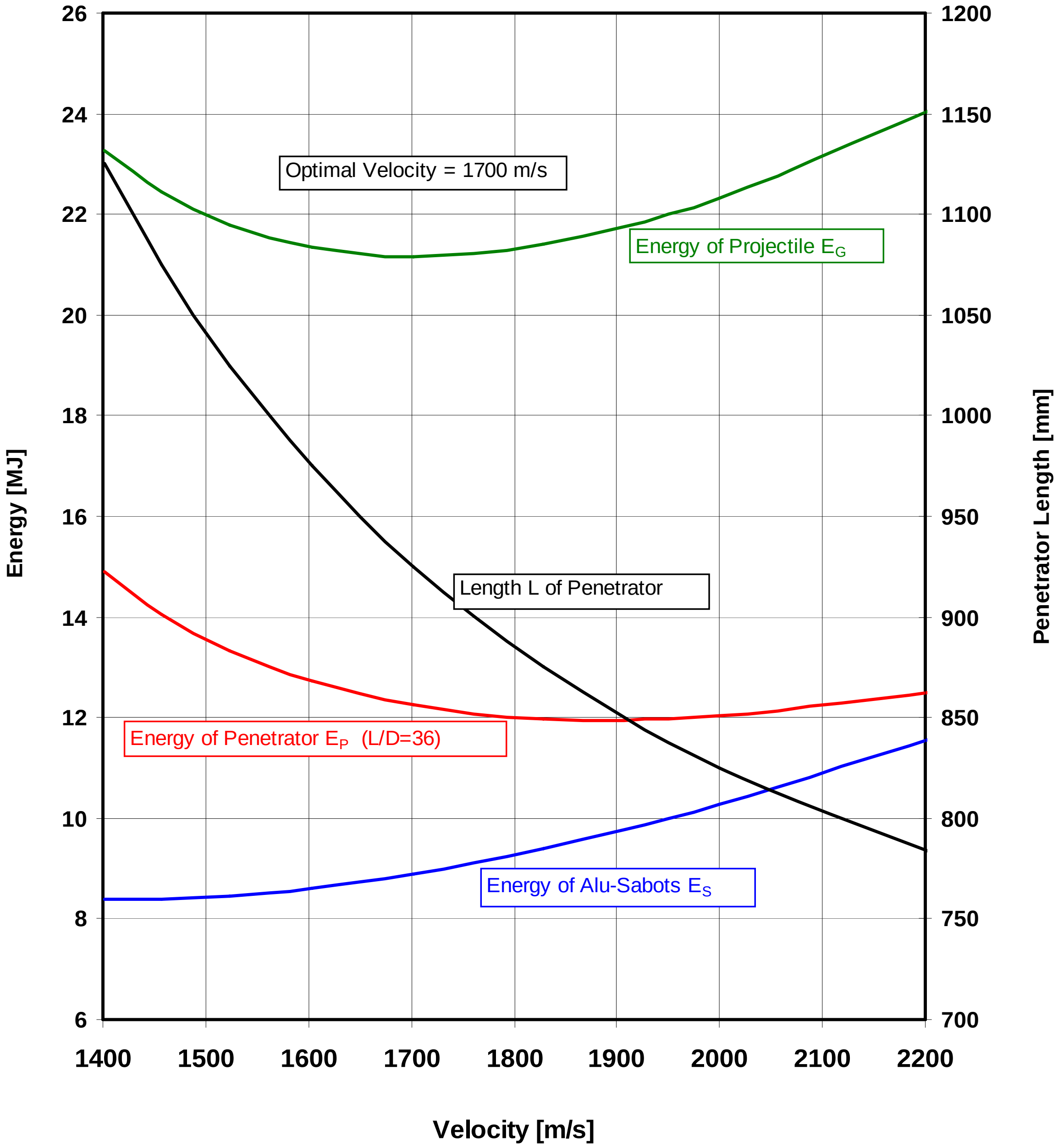

Figure 9 : Penetrators with 1000 mm RHA (800 N/mm^2 UTS / 60° obliquity) penetration limit
energy of projectile E_G = energy of penetrator E_P plus energy of sabot E_S
aspect ratio L/D = 36

The sum of penetrator E_P and sabot energies E_S is the total energy of the projectile E_G. Taking sabot mass into account obviously leads to a minimum energy shift to lower velocities, not depending on λ. The new optimum velocity is at v_T = 1700 m/s and again there is no distinct minimum. The total projectile energy variation is less than 2.5 % between 1580 and 1830 m/s.

3.3 External ballistics influence

The results presented so far refer to zero range, ie. at the muzzle. For a tactical range, typically 2000 m, the projectile velocity drop has to be considered. As shown in fig. 10 substantially more energy is required to keep a penetration limit of 1000 mm RHA.

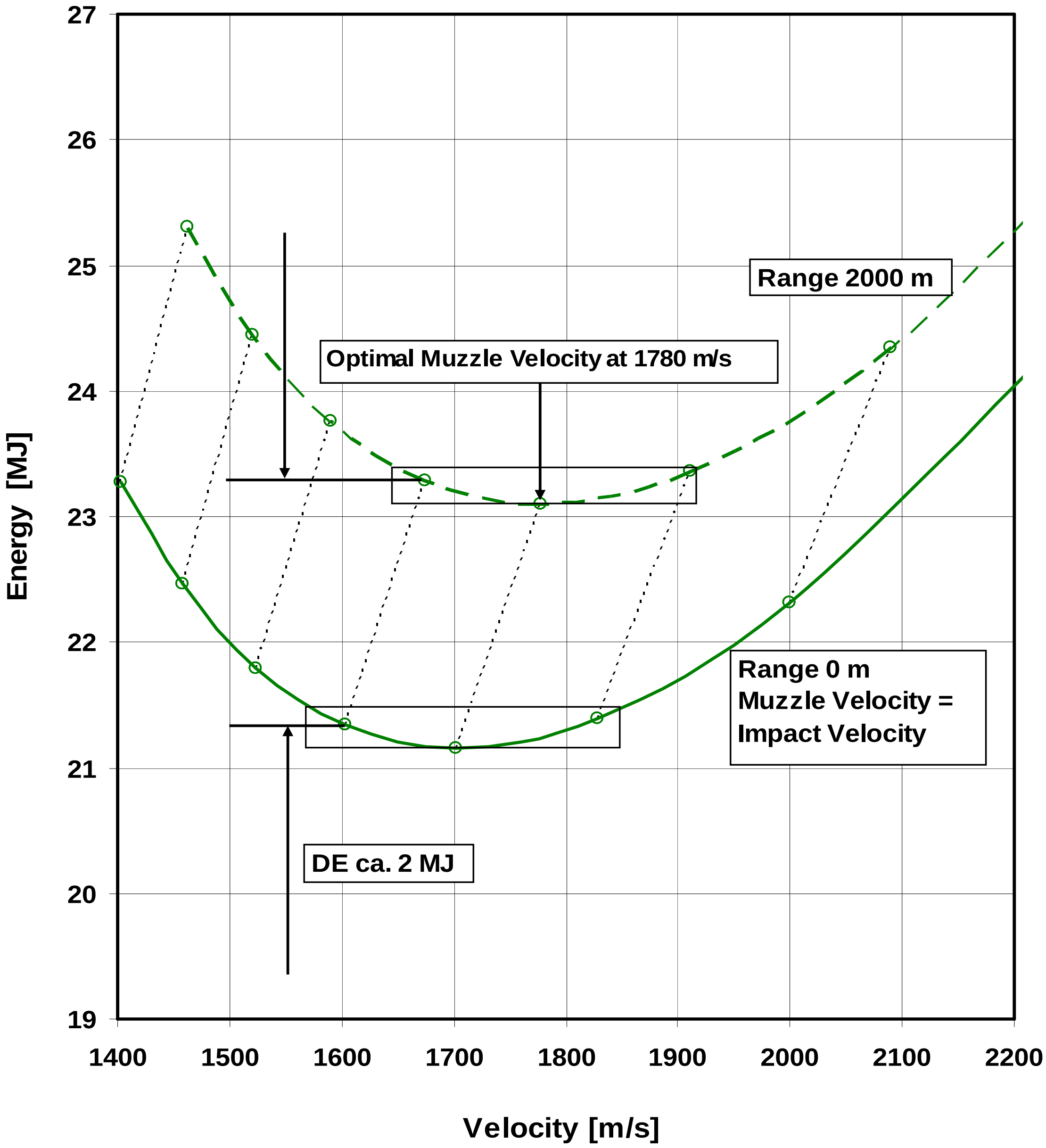

Figure 10 : Muzzle energy for projectiles
with 1000 mm RHA (800 N/mm^2 UTS / 60° obliquity) penetration limit
range 0 and 2000 m

Even though light and fast projectiles loose more velocity than slower but heavier ones the terminal ballistics are still better than expected. This is due to the Odermatt curves (fig. 5) becoming flatter at the upper end and due to sabot mass influence. In fact the energy loss is nearly constant over the entire scope apart from penetrator lengths extremes below 800 and above 1050 mm. The external ballistics influence reshifts the energy minimum to higher velocitites. In RHA plates of 800 MPa UTS this shift amounts to roughly 80 m/s, the optimum velocity then being 1780 m/s for 2000 m range.

3.4 Integration into a 140 mm high pressure gun

Tailoring the sabots as described is one important action, however to define the entire system the energy delivered by the gun has to match the minimum energy for obtaining the required penetration.
Fig. 11 shows the internal ballistics functions for a big caliber high pressure solid propellant gun (ca. 50 cal barrel length).

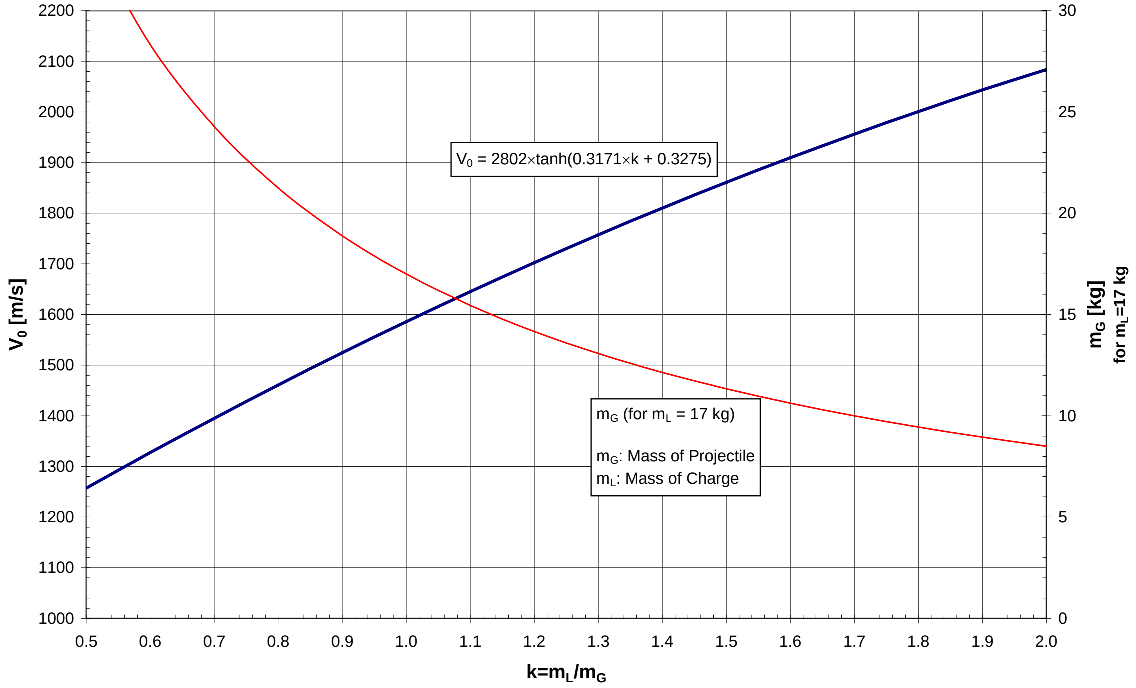

Figure 11

Depending on the propellant charge mass m_L to projectile mass m_G ratio the graph shows muzzle velocities and projectile mass for 17 kg charge mass corresponding to 85 MJ charge energy (combustible cartridge case included).
Transferring these curves to fig. 12 allows the selection of projectile layouts which reach 1000 mm penetration with 85 MJ energy input of a 140 mm / L50 gun at 7.5 kbar peak pressure.
Thus a rod of 1000 mm length and 36 aspect ratio penetrates 1000 mm RHA in front of the muzzle. The same penetration at 2000 m range will just be obtained by rod parameters lying on the intersection between the 85 MJ energy curve and the $\lambda = 40/2000$ m curve.
This intersection point represents a rod length of 900 mm and a muzzle velocity of 1830 m/s (lengths > 900 mm permit penetration > 1000 mm RHA).

Conclusions:
Conventional projectile technology requires very high aspect ratio rods to reach 1000 mm penetration in RHA targets even propelling them by a 140 mm gun with 85 MJ energy input.
Some margin for performance increase is at hand using

- jacketed penetrators as presented in [5] and
- new sabot design technologies

both of which lead to a considerable weight reduction.

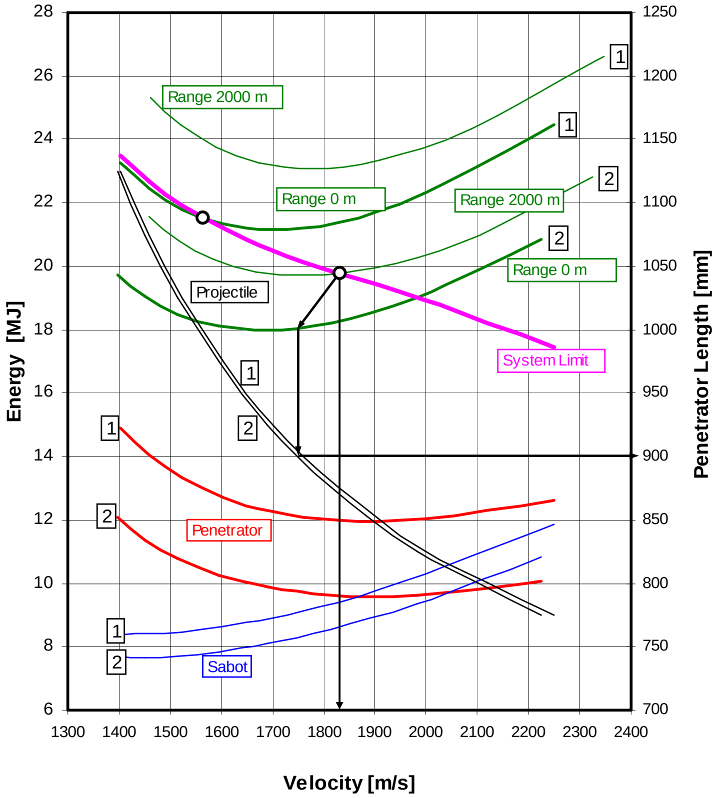

Figure 12 : Penetrators with 1000 mm RHA (800 N/mm^2 UTS / 60° obliquity) penetration limit aspect ratio = 36 [1] and 40 [2]

The terminal ballistics characteristics presented in [3] of solid propellant guns covering all conceivable projectile designs show a further typical optimum or maximum (see fig. 13).

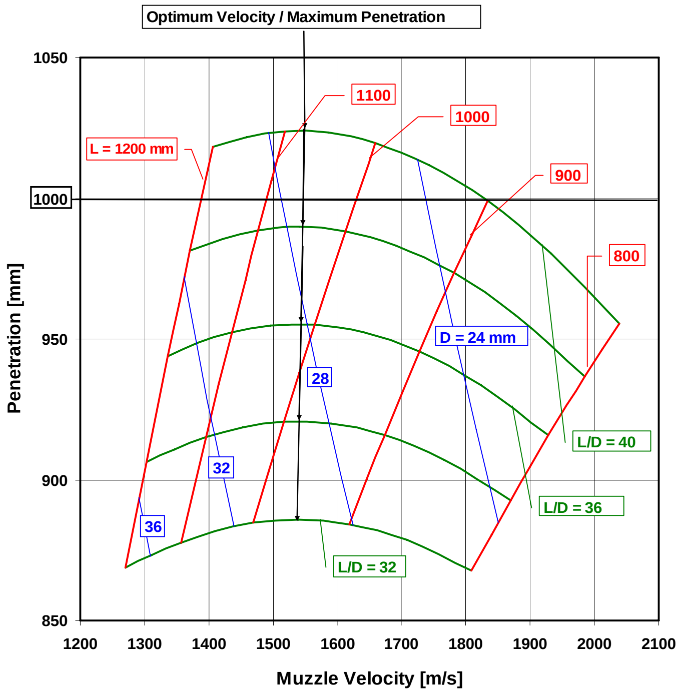

Figure 13 : Terminal ballistics characteristics for a 140 mm tank gun RHA (800 N/mm^2 UTS / 60° obliquity) / range 2000 m

For all penetrator aspect ratios there exists an impact velocity yielding maximum penetration. For 2000 m range this inherent velocity is around 1540 m/s, which can be confirmed analytically.
Referring to fig. 12 the same fact can be extracted from the common tangent of the gun energy curve and the appropriate λ-curve.

4. JACKETED PROJECTILES

Conventional high aspect ratio penetrators (λ > 30) have drawbacks such as pronounced elastic bending vibrations when leaving the muzzle and multiple ruptures in skirted targets leading to massive performance drops.
These drawbacks can be circumvented by jacketing a very slender heavy metal core with lighter material (preferably steel or titanium), see [ ].

Table 1 : comparison example

Densities : tungsten 17.5 $[g/cm^3]$ steel jacket 7.85 $[g/cm^3]$			
	penetrator		
	full core	jacketed	
Length L	960	960	
D	30	30	
$\lambda = L/D$	32	32	
core dia d_W	-	23.4	
$\lambda_W = L/d_W$	-	41	
core mass m_W (kg)	11.9	7.5	(inkl. Fins)
jacket mass m_H (kg)	-	1.9	
m_P (kg)	11.9	9.4	
m_P (%)	100	79	

For determining the masses of jacketed penetrators see fig. 14.

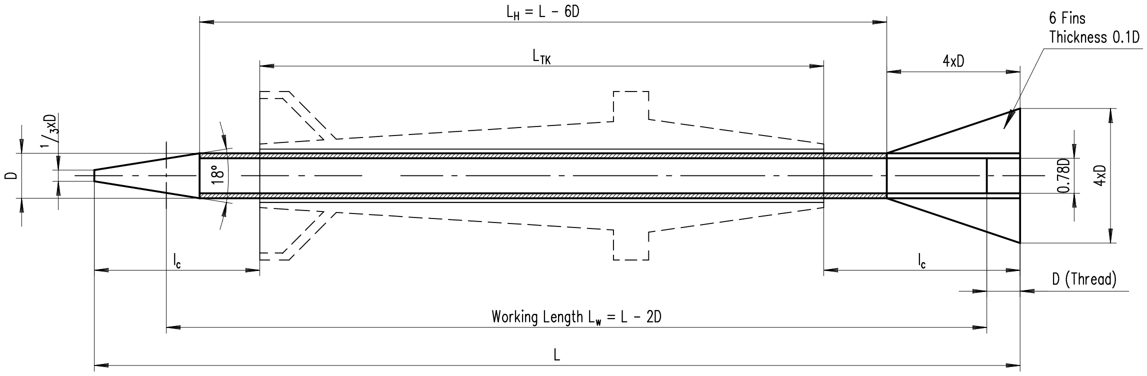

Figure 14: Proportions of steel/tungsten jacketed penetrators

Note that in the comparison both penetrator types are identical in length and outer diameter. Therefore the jacketed one is considerably lighter and contains correspondingly less kinetic energy for equal impact velocity. Despite of this fact a jacketed projectile attains practically the same penetration in thick RHA as its full core counterpart, as shown in [5].
This is due to the more favourable hydrodynamic behaviour of the tungsten/steel composite which yields a definitely smaller crater diameter, thus compensating the energy reduction, as shown in fig. 20 and [5].

Fig. 15 shows that a jacketed projectile with an overall aspect ratio of 36 reaches the 1000 mm penetration limit in RHA of 800 MPa UTS at 2000 m range.
The projectile length is (at least) 928 mm with a corresponding core aspect ratio of 46.

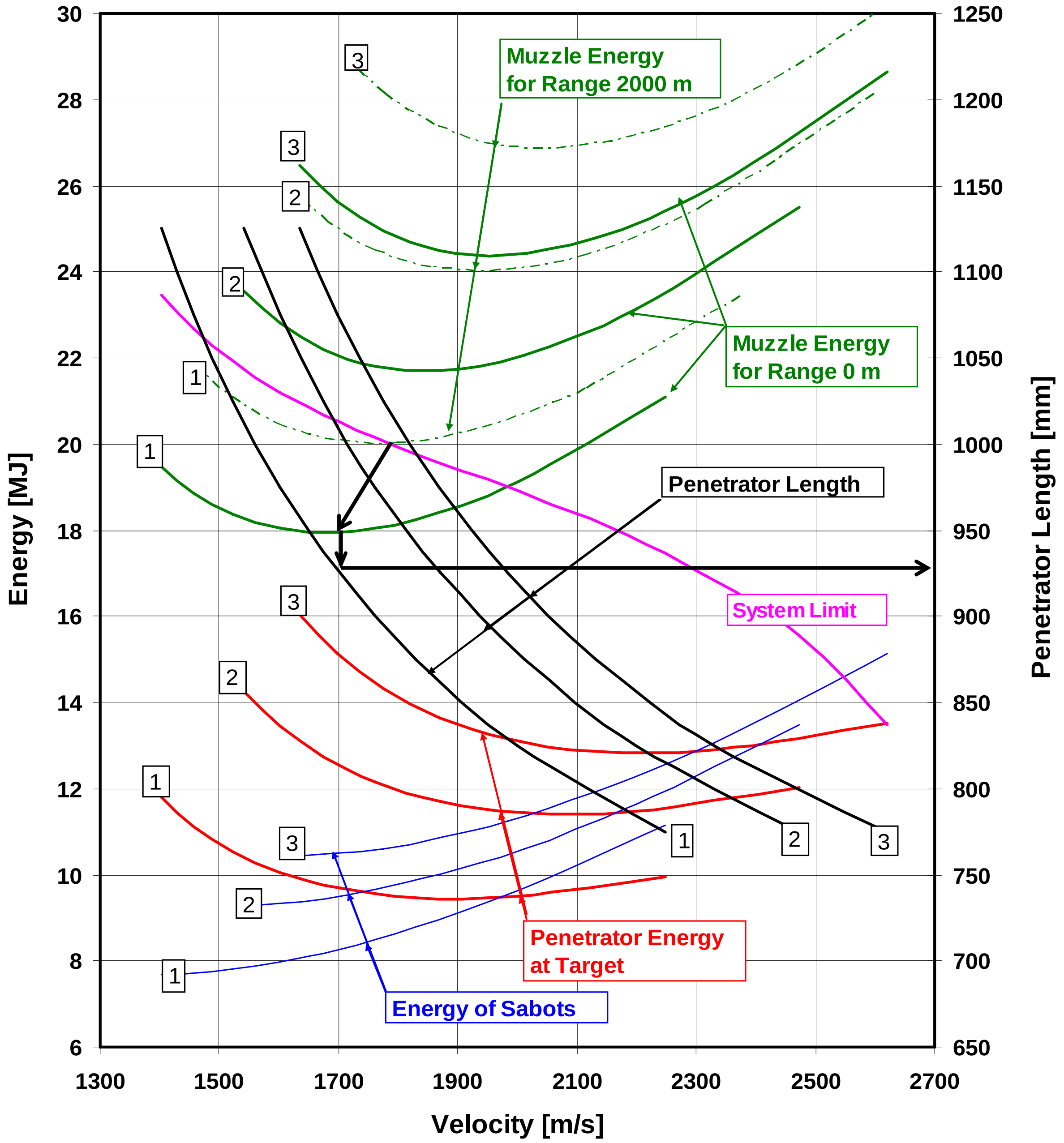

Figure 15 : Energies for 1000 mm penetration limit in RHA , 60° obliquity
[1] UTS of RHA 800 N/mm^2
[2] UTS of RHA 1000 N/mm^2
[3] UTS of RHA 1200 N/mm^2
System limit : muzzle energy of 140 mm gun, 85 MJ propellant energy

Obviously RHA targets with 1000 MPa UTS cannot be penetrated with λ = 36 jacketed penetrators, driven by conventional alu-sabots.

5. NEW SABOT TECHNOLOGIES

For more than 20 years now the same sabot material has been applied. It's time for a change. Various R+D departments work on this problem, but so far no new application has materialised in the big bore business.
Obviously the sabots designed according to fig. 8 are not optimised.
For a rough estimate of the influence of fiber reinforced plastic (FRP) sabot on system performance we assume a possible weight reduction of 25 - 30 %. In the calculation this is simply accounted for by taking a density of 2.0 instead of 2.7 g/cm^3.
To evaluate the ultimate (theoretical) performance increase we set the density at zero. These results are presented in fig. 16
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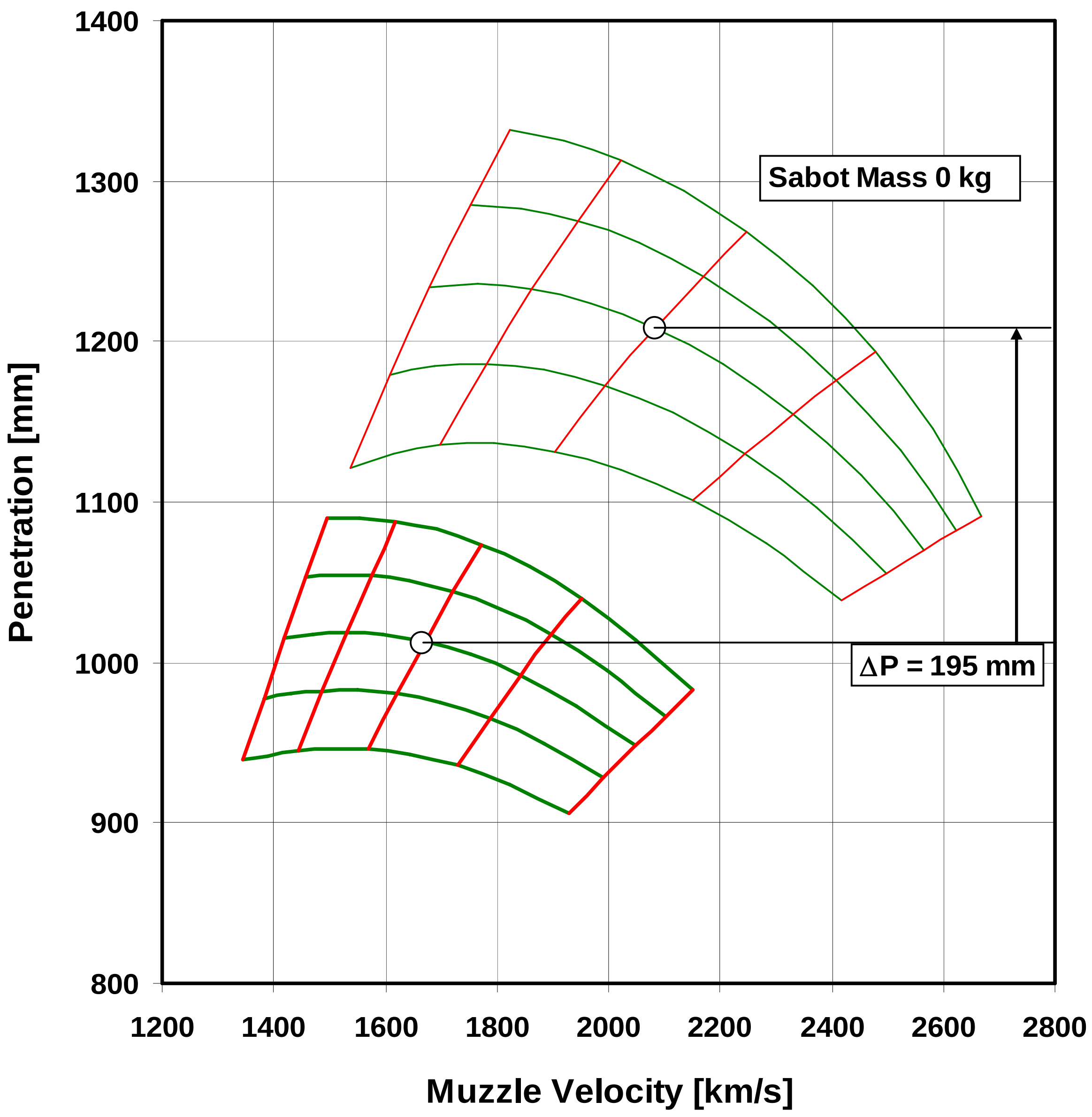

Figure 16 : Terminal ballistic characteristics for penetrators with aluminium sabots and "zero mass" sabots

The graph shows in one example an increase of 195 mm penetration for a rod (L = 1000, $\lambda = 36$) with "zero mass" sabot. In reality only about 30 % of that can be exploited, i.e. ~ 60 mm, corresponding ~ 6 %, referring to 1000 mm RHA.

6. ARMOR PLATE STRENGTH INFLUENCE ON OPTIMUM VELOCITY

In item 2.2 the influence of target plate strength has been derived analytically.
The higher the target UTS the higher the optimum velocity will be.
For 800 MPa UTS the optimum velocity is 1900 m/s, rising to 2200 m/s for 1200 MPa UTS.
The overall system investigation yields very similar results as shown clearly in the terminal ballistic characteristics for 2000 m range (see figs. 17 to 19).
However it has to be noted that all these system optima are situated distinctly below the generally cited level of far above 2000 m/s.
As also shown in fig. 15, the UTS influence nevertheless is quite significant (fig. 17 to 19).

- Whereas a target UTS of 800 MPa allows 1000 mm perforation at 2000 m range with L/D = 33.3 jacketed penetrators of 950 mm length and 1750 m/s muzzle velocity,
- a target UTS of 1000 MPa requires L/D = 38.5, 950 mm length and 1900 m/s muzzle velocity;
- a target UTS of 1200 MPa even requires L/D = 41.8, 1000 mm length and 1900 m/s muzzle velocity; this extreme layout is by far out of reach for todays technologies even for a 140 mm high pressure solid propellant gun system.

7. REFERENCES

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Craters Caused by Jacketed Heavy Metal Projectiles of very high Aspect Ratio impacting Steel Targets
16th International Symposium on Ballistics, San Francisco 1996

140 mm Gun , 85 MJ Propellant Energy :

Terminal Ballistic Characteristics for Jacketed Penetrators and FRP Sabots
RHA Plates , 60° Obliquity , Range 2000 m

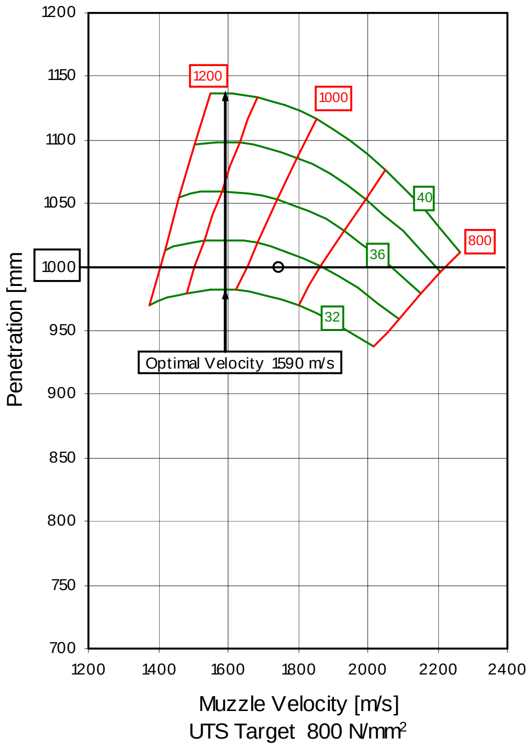

Figure 17 : 1000 mm penetration: L=950 mm, L/D=33.3

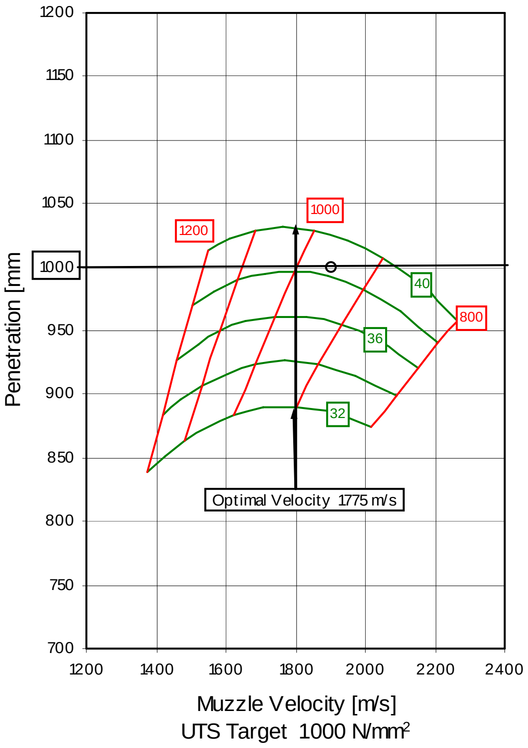

Figure 18 : 1000 mm penetration: L=950 mm, L/D=38.5

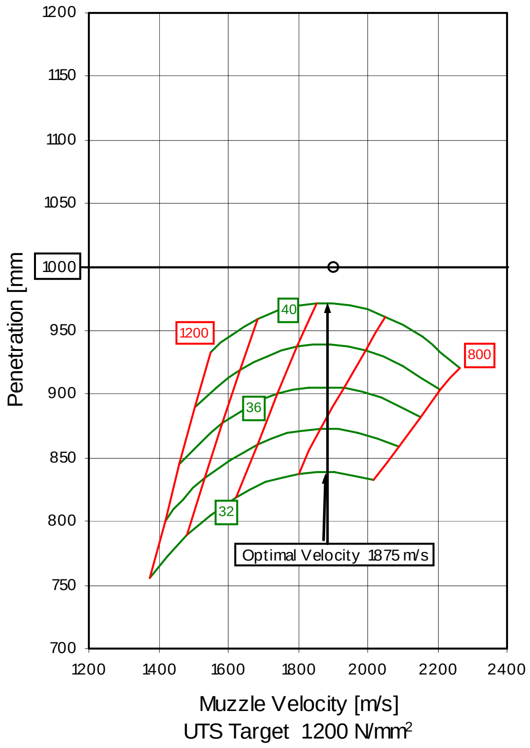

Figure 19 : 1000 mm penetration: L=1000 mm, L/D=41.8

Comparison of impact craters: Full core tungsten penetrators and steel/tungsten jacketed penetrators with the same impact velocity in the same RHA plate (800 MPa UTS)

Tungsten penetrator	Steel/tungsten jacketed penetrator
∅ 22 x 680	∅ 22/17 x 680
mean crater dia = 46.1 mm	mean crater dia = 40.75 mm
impact velocity 1850 m/s	impact velocity 1850 m/s

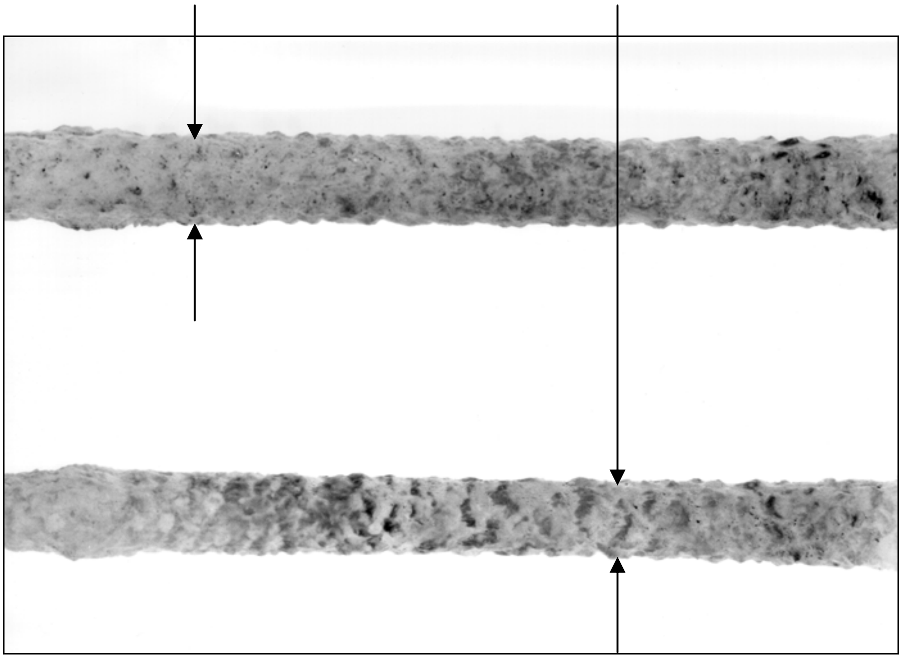

Figure 20 : Impact craters in RHA (800 MPa UTS)