

# PENETRATION LIMITS OF CONVENTIONAL LARGE CALIBER ANTI TANK GUNS/KINETIC ENERGY PROJECTILES

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The following systems analysis gives the functional relation between the projectile muzzle velocity,  $v_0$ , from a given weapon and the achievable penetration  $T$ , when the major ballistic parameters are considered. The goal is to develop a penetrator with respect to mass and velocity with a given rod length to diameter ratio,  $L/D$ , to obtain a penetration maximum in the homogeneous steel target. The 140 mm solid propellant gun will be discussed as a particular case. Maximum penetration will be calculated for the calibers of 105, 120, and 140 mm using more energetic propellant, longer cannon tubes, and minimized sabot mass.

## 1. SYSTEM DESCRIPTION

The following drawing shows all parameters of the known gun / KE system:

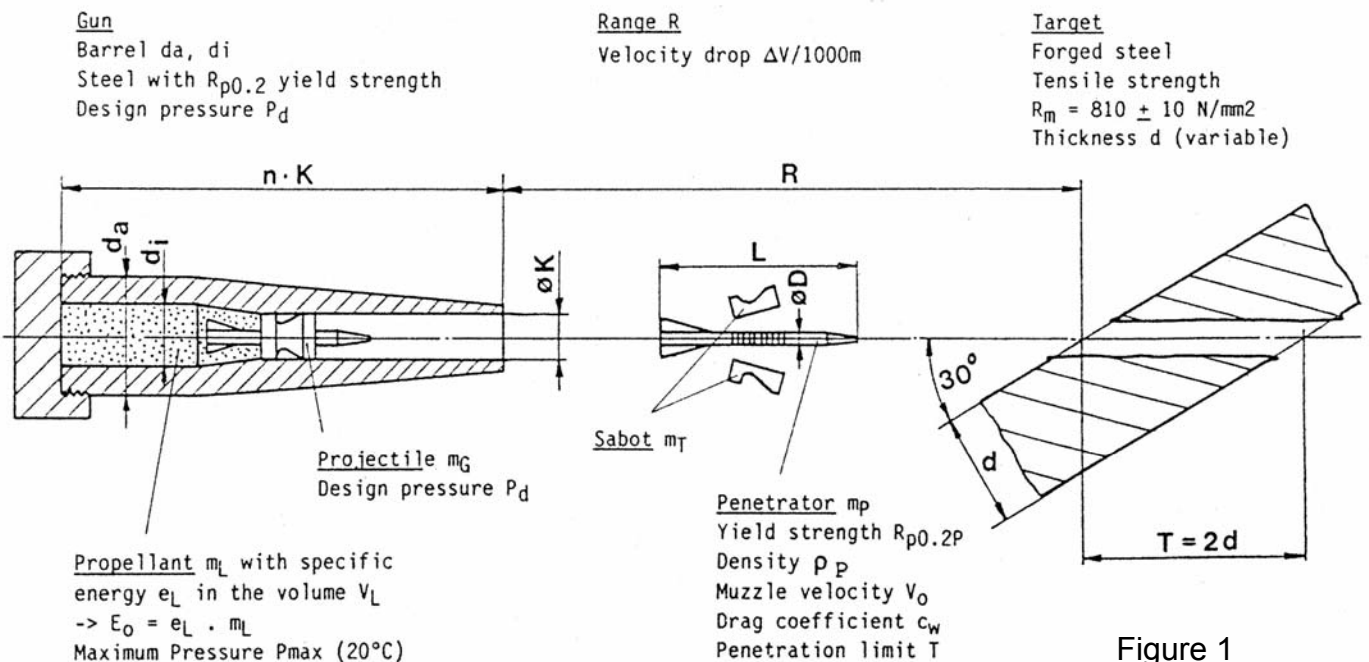


Figure 1

## 2. TERMINAL BALLISTICS

In contrast to other ballistic institutes who use arrays of thick armor plates to determine maximum penetration, we prefer to measure the critical angle  $\theta_{50}$  (50% penetration probability) in a thick armour plate. The  $\theta_{50}$  angles of 41 firing test with 8 highly differing penetrators are now available for the following analysis. The experimental parameters with respect to caliber, penetrator and target properties for the firing tests fall within the following limits:

- Calibers	105, 120, 140 mm
- Penetrator properties	
Lengths $L$	330 - 900 mm
Diameters $D$	22 - 32 mm
Length to diameter ratios $L/D$	11 - 32
Rod densities $\rho_P$	17000 - 17750 kg/m <sup>3</sup>
Rod impact velocities $v_T$	1100 - 1900 m/s
- Target properties	
Plate thicknesses $d$	150 - 400 mm
Tensile strengths $R_m$	800 - 1000 N/mm <sup>2</sup>
$\theta_{50}$ -angles (obliquity referred to the normal)	30 - 74 °
Density $\rho_T$	7850 kg/m <sup>3</sup>

An empirical dimensionless penetration relation could be deduced from the results of the 41 tests. The formula is derived with empirical assumptions and consideration of analytical boundary conditions. This formula is valid for  $L/D \geq 10$ .

$$\textcircled{1} \quad \frac{d}{D} = a \left( \frac{L}{D} \right) \cdot \cos^{0.745} \Theta \cdot \sqrt{\frac{\rho_P}{\rho_T}} \cdot e^{-\frac{25.9 \cdot R_m}{\rho_P \cdot v_T^2}}$$

where:

$$a \left( \frac{L}{D} \right) = \frac{L}{D} + 3.77 \cdot \left( 1 - \tanh \frac{\frac{L}{D} - 10}{6.89} \right)$$

The rod length,  $L$ , is defined by the distance from the rod conic point center of mass to the rod end plane minus the rod diameter  $D$ . The decrease in length is the observed rod residual length for critical angle penetration.

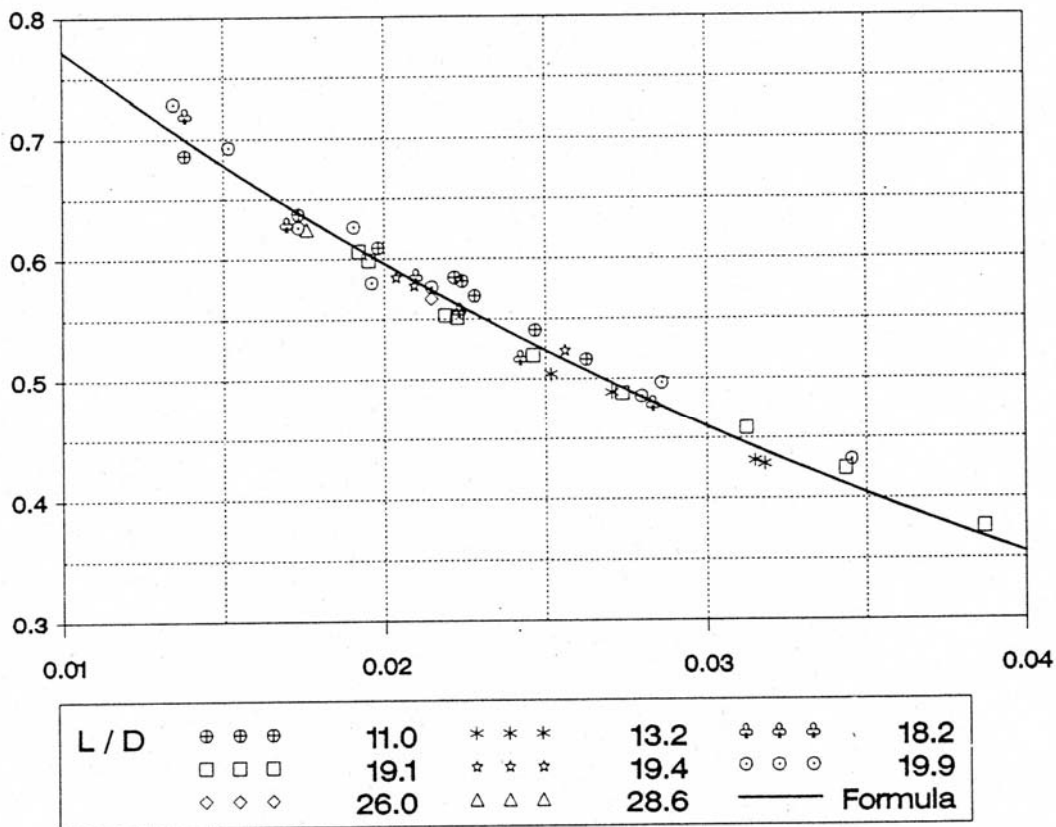
For  $L/D \geq 20$  the expression  $a(L/D)$  transforms to  $L/D$ . That means the penetrable plate thickness is directly proportional to the penetrator length, and no longer a function of  $L/D$ .

The formula simplifies to pure hydrodynamic penetration in the limits of large impact velocities and normal incidence, ( $\theta_{50} = 0^\circ$ ):  $d = L \cdot (\rho_P/\rho_T)^{0.5}$ . The results of the 41  $\theta_{50}$  penetrations are shown in dimensionless form in the diagramm 1.

The graph axes were chosen as:

$$\text{x-axis: } \frac{R_m}{\rho_P \cdot v_T^2} \qquad \text{y-axis: } a \left( \frac{L}{D} \right)^{-1} \cdot \cos^{-0.745} \Theta \cdot \sqrt{\frac{\rho_T}{\rho_P}} \cdot \frac{d}{D}$$

Diagram 1:



The correspondence between experiment and the formula is good. The maximum differences are only 5% and the standard deviation is 2.4%.

The advantages of measuring the  $\theta_{50}$  angle are now apparent: Material properties, rod geometries, and/or impact velocities can be compared to each other. The penetration  $T$  of a rod can be easily estimated prior to firing tests, and extrapolations to other velocities are possible to a fairly high degree of accuracy.

The results given in chapter 6 are based on a target with a yield strength of  $810 \text{ N/mm}^2$ ,  $\theta_{50} = 60^\circ$  degrees and with variable plate thickness,  $d$ . The penetrator lengths in the diagram are given by the cylindrical rod portion. This length was reduced by the penetrator diameter in the penetration formula as indicated above.

### 3. EXTERNAL BALLISTICS

The velocity loss due to drag during the projectile flight is relatively small with rods. Consequently detailed calculations were not carried out. The loss was calculated by an approximate formula using the constant air density,  $1.225 \text{ kg/m}^3$ . When the parameters of muzzle velocity, mass, length of the penetrator, as well as the fin cross sections are considered, the calculated velocity drop is in the range of 50 to 90 m/sec per 1000 m.

Computations conducted to determine first round hit probability (FHP) with heavy/slow, and light/fast penetrators showed no appreciable differences. When the cannon was directed by a fire control system, no noticeable accuracy differences were noted for the two rod types at a standard firing distance of 1500 meters. For the useful tactical range (3000 m) the FHP of the heavy penetrator reduced by 2% for stationary targets and 5% for moving targets. Thus one can say that external ballistic performance is practically independent of penetrator layout.

### 4. INTERIOR BALLISTICS: CONSIDERATIONS FOR SABOT MASS CALCULATION

#### 4.1 The Function "Projectile Mass $m_G$ / Muzzle velocity $v_0$ "

Given is a projectile  $m_G$  in a 140 mm L 47 cannon, designed for 7000 bar maximum pressure, charged with a grain propellant of mass  $m_L = 15 \text{ kg}$  and a specific energy of  $4300 \text{ J/g}$ ; the maximum gas pressure at  $20^\circ\text{C}$  is 5500 bar.

The achievable muzzle velocity with various projectile masses  $m_G$  can be calculated with conventional procedure with appropriate choice of propellant geometry. The mass of the projectile is varied in the large range  $9 \text{ kg} < m_G < 20 \text{ kg}$ . The results are presented in the continuous  $m_G - v_0$  curve in diagram 2.

#### 4.2 Dimensions/Proportions of Penetrator and Sabot [1,2]

The next problem is the calculation of sabot mass  $m_T$ , appropriate for the penetrator with mass  $m_P$ , which together give the total projectile mass  $m_G$ . For this purpose three penetrator zones are differentiated, namely

- a compressive zone  $L_c$  in the forward rod section; mass  $m_c$
- a tensile zone  $L_t$  in the rear portion of the rod; mass  $m_t$ , and
- a shear zone  $L_s$  between  $L_c$  and  $L_t$  in which the acceleration forces are transferred from the sabot (also with length  $L_s$ ) to the rod.

These zones are shown in figure 2 on the next page.

The determination of the maximum acceleration,  $b_{max}$ , is of importance to this problem:

2

$$b_{max} = \frac{\pi \cdot k^2 \cdot p_{max}}{4 \cdot m_b}$$

$k$  = caliber

$p_{max}$  = max permissible pressure

$m_b$  =  $m_G + 0.5 \cdot m_L$  = accelerated mass

When  $R_{p0.2\%}$  is the yield strength and  $\rho_p$  the density of the penetrator material, the acceleration force  $b_{max} \cdot m$  forms boundaries (in the simplified cylindrical rod without fins) which define the lengths  $L_c$  and  $L_t$  as follows:

$$\sigma_{max_{zul}} = R_{p0.2\%} = \frac{b_{max} \cdot m_c}{0.25 \cdot \pi \cdot D^2} \approx \frac{b_{max} \cdot m_t}{0.25 \cdot \pi \cdot D^2} = \frac{b_{max} \cdot 0.25 \cdot \rho_P \cdot L_c \cdot D^2}{0.25 \cdot \pi \cdot D^2}$$

3

$$L_c \approx L_t = \frac{R_{p0.2\%}}{b_{max} \cdot \rho_P}$$

The density  $\rho_p$  is substituted in the formula as  $17 \text{ g/cm}^3$  and the yield strength as  $1300 \text{ N/mm}^2$ . The same calculation is made later for  $R_{p0.2\%} \geq 1500 \text{ N/mm}^2$  to describe the increased performance system.

Penetrator materials have been subject to rapid development for the past 20 years. However sabot materials technology has been at a practical standstill. The same aluminium alloy, AlZnMgCu, with an allowed shear strength of 250 N/mm<sup>2</sup> has always been used. In fact for long rods with  $L/D > 20$  the sabot shear tension is not critical, if a uniform distribution of the shearload is assumed (which is not the case in reality). Rather the weak link of the system is the tungsten yield strength in both the front and rear "overhang" with length  $L_t$ ,  $L_c$ .

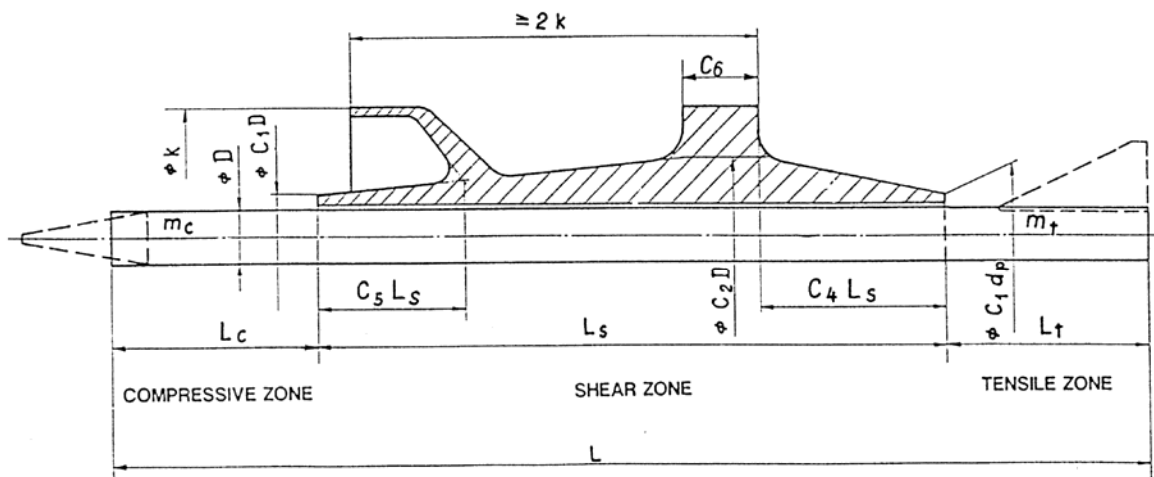
The length of the sabot then becomes

4  $L_s = L - L_t - L_c$

There is little doubt that one of the next KE munitions improvements will see the application of a new, lighter material, so that the "deadweight" of the projectile can be decreased. Our calculation shows that appropriate composite materials can reduce sabot weight by 30% compared to the standard aluminium designs.

The proportions of the Aluminium sabots which were entered in our systems calculations are shown in the figure 2 below.

Figure 2



The  $m_p - v_0$  values in diagram 2 were obtained by iterative calculations of  $m_T$  for an assumed  $m_p$  with a CAD program.

## 5. SYSTEMS CALCULATIONS FOR 140 MM CALIBER

By application of the exterior and interior ballistic equations in sections 2 and 3 we derive the  $v_0 - T$  - functions, which are also represented in diagram 2 for the case  $L/D = 32$ .

The question of the penetration maximum for a given gun caliber is also answered in this calculation:

The maximum penetration for  $L/D = 32$  is almost 800 mm and is achieved with a penetrator of approximately  $m_p = 7$  kg, with a total round mass  $m_G = 12,6$  kg, and a muzzle velocity of 1730 m/sec, but the maximum is not sharp.  $T$  only varies by  $780 \text{ mm} \pm 20 \text{ mm}$  in the wide velocity range 1500 to 1960 m/s.

Thus the muzzle velocity is not dominant for the long rod penetration power for a given weapon and energy input.

Therefore other penetrator design criteria can be considered for the final design:

- High system efficiency, high energy  $E_P$  of the penetrator
- High bending stiffness of the penetrator to achieve a high resistance to fracture

These criteria lead to slow and heavy penetrator designs. Other criteria such as

- Short time of flight
- minimal volume and mass for ease of handling
- behaviour in special targets

on the other hand lead to light high velocity penetrator designs.

Our present designs today are clearly preferred to the left of the maximum, but the maximum itself is surely not a bad solution. Some experimental 140 mm projectiles are marked by a triangle in diagram 2.

Diagramm 3, "Terminal Ballistic Characteristics", shows all projectiles with velocities from 1460 m/sec to 2130 m/sec, L/D ratios from 20 to 44, and their achievable penetrations for 3000 m range.

## 6. COMPARISON OF IMPROVED PERFORMANCE 105/120/140 MM GUNS

The same calculations are now made for the following variations:

140mm L47	$m_L = 15 \text{ kg}$	$e_L = 5000 \text{ J/g}$	$P_d = 8000 \text{ bar}$	$L_{\max} = 950 \text{ mm}$
105mm L60	$m_L = 6 \text{ kg}$	$e_L = 4300 \text{ J/g}$	$P_d = 6300 \text{ bar}$	$L_{\max} = 750 \text{ mm}$
120mm L55	$m_L = 7.8 \text{ kg}$	$e_L = 5000 \text{ J/g}$	$P_d = 7500 \text{ bar}$	$L_{\max} = 850 \text{ mm}$

$L_{\max}$  is the maximum permissible length of the penetrator.

These design variations are calculated with 30% sabot weight decrease, and tungsten rod penetrators with  $R_{po.2p} > 1500 \text{ N/mm}^2$ .

The results are shown in diagram 4 for L/D ratios from 32 to 36.

The comparison shows a considerable jump from 120 mm to 140 mm, due to the doubling of energy-input, and it shows for all three calibers the performance pinnacle. The 140 mm gun will be very probably the last conventional solid propellant design for antitank purposes which fits in actual heavy tanks, when gun steel with very high yield strength is applied. If the progress in armor protection should require still more powerful antitank-means, a new accelerator technology with considerably higher energy-density has to be developed.

## 7. REFERENCES

- [1] Structural design considerations for minimum weight sabots  
William H. Drysdale, R.D. Kirkendall, L.D. Kokinakis  
USARRADCOM Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005
- [2] CAD/CAM Implementation in kinetic energy projectile design  
Brett Soerensen, Ballistic Research Laboratory, US ARMY



Diagram 2

**Caliber 140 mm**

Mass of Projectile  $m_0$ , Mass of Penetrator  $m_p$   
vs. Muzzle Velocity  $v_0$

Penetration T  
for  $P_d = 7000$  bar and  $L/D = 32$   
Range 3000 m

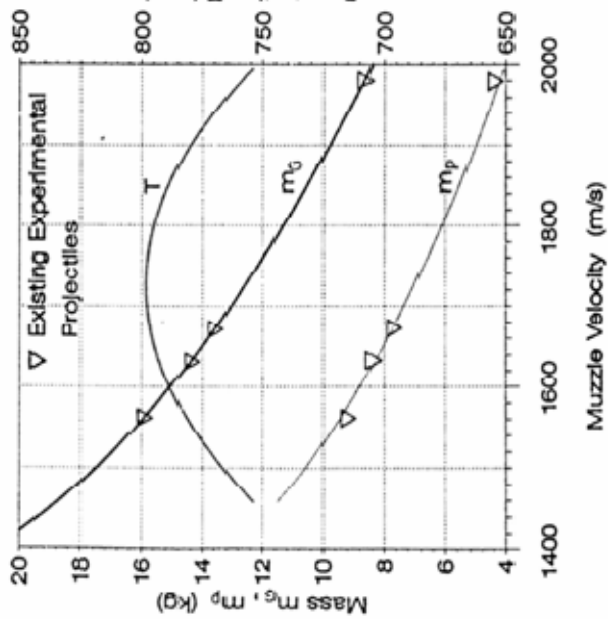


Diagram 3

**Caliber 140 mm**

Terminal Ballistic Characteristics

$P_d = 7000$  bar ; Alu-Sabot  
0.2% - Yield of Tungsten  $\approx 1300$  N/mm<sup>2</sup>  
Target : Steel Rm = 810 , 10 N/mm<sup>2</sup>  
Range 3000 m

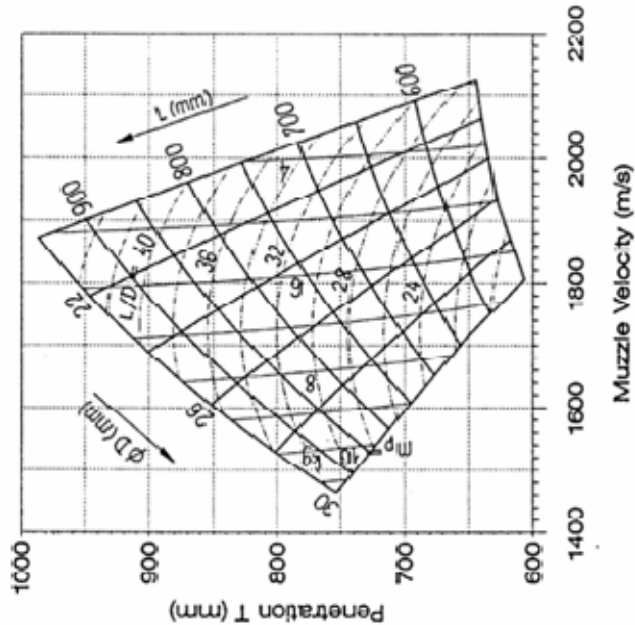


Diagram 4

**Comparison of Improved Tank Guns**

Composite Sabot  
 $32 \leq L/D \leq 36$   
Range 3000 m

