KINETIC ENERGY PROJECTILES:

DEVELOPMENT HISTORY, STATE OF THE ART, TRENDS

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This paper describes the main development steps of KE projectiles from the basic full calibre antitank steel round to today's heavy metal sub-calibre penetrators having an aspect ratio of 30, along with the corresponding penetration performance increase. A plausible development trend will be jacketed heavy metal rods having aspect ratios of 40 plus. Penetration results of big calibre firing tests with monoblock and jacketed penetrators are presented. The conclusion is that both projectile types yield the same penetration for the same rod length and the same velocity.

INTRODUCTION

At present the penetration performance of big calibre heavy metal KE projectiles exceeds 600 mm in RHA by far, as illustrated in Fig. 1.

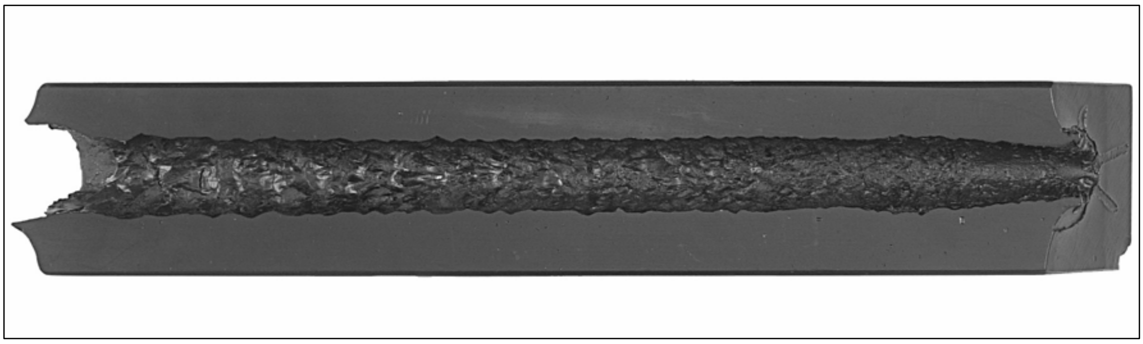

FIGURE 1. Tungsten rod penetration in a 400 mm thick RHA plate of 260 HB hardness, obliquity 53° NATO (1994 test in Thun)

Astonishingly a very similar result had been achieved 50 years ago in the US (Fig. 2)

Shortly after WWII in the Naval Proving Ground at Dahlgren, Virginia, a steel projectile of 406 mm calibre neatly penetrated a 26" thick armour plate "without deformation".

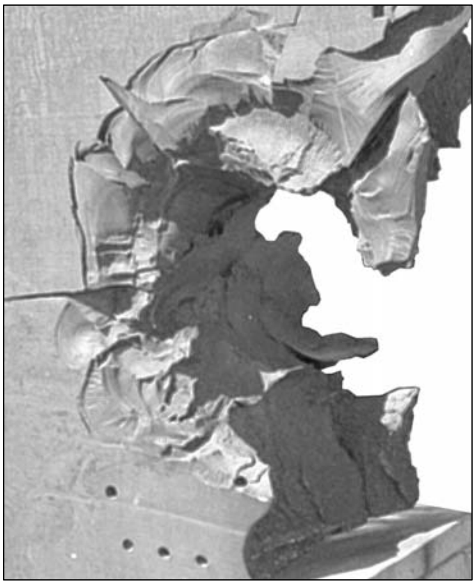

FIGURE 2. Penetration of a 26" thick armour plate by a steel projectile of 406 mm calibre

(Photo by Dr. C. Lanz)

The ballistic data comparison of these two tests show the development progress of antitank KE projectiles within the past 50 years:

	1950	1994	ratios 1994/1950
penetration P (mm RHA)	660	660	1:1
bore diameter (mm RHA)	~ 400	~ 44	1:9.1
bore volume (cm^3 in RHA)	~ 83000	~ 1000	~ 1:83
projectile mass (kg)	1000	4.7	1:213
projectile velocity (m/s)	~ 800	~ 1600	2:1
projectile energy (MJ)	320	6	1:53
propellant energy (MJ)	1000	40	1:25
bore volume per unit projectile energy (cm^3 RHA/MJ)	260	167	1:1.56
specific penetration (P/Calibre)	1.63	5.5	3.37:1

The last two reference values are of special interest:

- On one hand the specific penetration of KE projectiles shows a massive increase from around 1.6 to at least 5.5 calibres. This value approaches the specific penetrations heretofore reached by shaped charges only.
- On the other hand the specific bore volume is about 1.5 times less than 50 years ago.

The following section describes the main development steps between the two milestones mentioned above. There will be no presentation of exact historical data, but a general compilation of the principal technological advances and their theoretical basis leading to today's state of the art. For more details see [1].

DEVELOPMENT HISTORY

In the 1917 edition of the well known textbook "Lehrbuch der Ballistik" by Carl Cranz terminal ballistics are not treated extensively. There is the calculation of the projectile energy needed to put a man or a horse out of action, however the purpose of the cap on an armour piercing round is mentioned as well. Such full calibre steel projectiles very often featured a cap and a ballistic ogive as state of the art, astonishingly up to the fifties (Fig. 3A + 3B). During WW II terminal ballistics (projectile / target interaction) research was intensified to allow the development of KE rounds with increased penetration.

An obvious approach may have been the idea to focus the projectile energy onto a small diameter in order to reach a high penetration, taking the proportionality of energy and perforation volume into account.

This idea was realised by designing the so-called APHC, armour piercing hard core round (in German "Panzerkerngeschoss"). In essence, APHC projectiles consist of a hard, sub-calibre core within a light alloy body. In consequence, most of the kinetic energy imparted to an APHC projectile is concentrated in the sub-calibre core and hence on a smaller area of the target. This, together with the high hardness of the core, leads to greater armour penetration than that achieved with full calibre AP projectiles fired from the same gun. At the beginning sub-calibre cores or penetrators have been made of steel, surrounded by aluminium (Fig. 3C). Later tungsten carbide metal cores were used which have a considerably higher density and hardness than steel.(Fig. 3D). Compared to the full calibre round the APHC core energy is considerably lower, but this drawback is more than compensated by the significantly higher velocity due to the reduced mass. Moreover the time of flight to target is shorter and the sighting range greater. These facts are very helpful when engaging moving targets.

The next development step, a very demanding one, was to design a radially sectioned lightweight sabot. At the muzzle the sabot is separated from the core (Fig. 3E).The drastically reduced cross section results in a much better exterior ballistics behaviour.

Projectile energy was increased further by replacing carbide metal (ca. 15 g/cm^3 density) by tungsten or depleted uranium (ca. 18 g/cm^3 density).

Of course with an APDS (armour piercing discarding sabot) round a wide area in front of the muzzle is endangered by the relatively heavy sabot segments, yet most armies take this risk. However, the spin stabilised APDS is an expensive affair with a mediocre performance, piercing only 2.5 to 3 calibres of armour steel. All the more so when comparing this to shaped charges which penetrated 4 calibres as early as 1950. In fact France has refrained from fielding APDS ammunition for the 105 mm AMX 30 tank and ordered shaped charge rounds exclusively. This "obus G" had a low spin rate shaped charge since it contained ball bearings in the spin stabilised round. In other countries as well the shaped charge, hardened for the acceleration in high pressure tank guns, competes with APDS. As opposed to the complicated "obus G" the far simpler "sliding" driving band was used to keep the shaped charge from turning, stabilisation being provided by fins.

In the end this stabilisation method is the key to a decisive development breakthrough in KE technology, since spin stabilisation limits the penetrator aspect ratio to a maximum of 5. The Russians were the first to realise this elegant solution in mass production. The 115 mm calibre was new as well, the steel core was more than 400 mm long with approx. 40 mm diameter (Fig. 3F). Guidance in the smoothbore barrel was provided by a short three-piece steel sabot and by the edges of the fins. This was the forerunner of the modern KE projectile.

Thus the T 62 tank's main armament was a technology milestone. Yet it was far from being perfect. Later, terminal ballistics research progress proved the great penetration increase using heavy metals instead of steel, especially for velocities above 1200 m/s [2, 3]. Comparing the fin stabilised steel rod with the spin stabilised heavy metal APHC the former penetrates only a 3 calibre length despite its elegant outline. In the West further development was therefore clearly vectored towards long tungsten heavy metal rods. At the beginning the strength of sintered tungsten was low, the slender rod had to be supported by a high strength steel jacket (Fig. 3G). But soon the needed strength was found, sintering tungsten together with nickel, iron and cobalt or alloying uranium with titanium. Then jacketing was no more necessary, the first monoblock projectile emerged in 1976.

Their aspect ratios were between 10 and 15 (Fig. 3H). Astonishingly the Russians adhered to the cheap steel rod for a long time, even though using a 125 mm calibre and the considerable rod length of some 550 mm.

On the other hand the use of heavy metals is compulsory, as shown before. Theoretical considerations require that the projectile has to be

- as long as possible in the first place
- as fast as possible in the second place.

These developments are in full swing. Taking the 105 mm calibre the core dimensions of previously 30 dia x 300 shifted to 25 dia x 500 and to 20 dia x 600 in the latest designs, having an aspect ration of 30. The latter dimensions attain around 5 calibres penetration length, about double the original APDS performance, with hardly altered internal ballistics.

Improved internal ballistics would allow 6 calibres penetrations heretofore reached by shaped changes only.

The key to this progress is materials technology, see Table 1

TABLE 1

Development generation Year	1 1970	2 1978	3 1985	4 1995
Tensile strength R_m (N/mm^2) Yield strength $R_{P0.2}$ (N/mm^2) Elongation at break A_5 (%)	800 ≈ 650 1 - 4	1200 1000 ≈ 6	1450 1400 ≈ 8	1700 1650 ≈ 8

The table shows the progress in materials technology by optimising additive contents of nickel, iron, cobalt, copper and manganese, as well as by optimising the production process. Within 25 years the yield strength was more than doubled.

Similar steps can be observed in depleted uranium technology (which is banned in some countries, e.g. Germany and Switzerland):

Approximately the same tensile strength is achieved by alloying 0.75% Titanium, but typically the elastic limit is less marked and the Young's modulus is by far lower for DU. (120 GPa versus 360 GPa for Tungsten). DU-penetrators therefore need stiffer and heavier sabots than tungsten rods, which compensates the slightly better impact behavior of DU in RHA.

STATE OF THE ART, TRENDS

As mentioned before at the present time KE projectiles with rods of tungsten or depleted uranium (DU) are in the inventories throughout the world or are being fielded. These rods have an aspect ratio of around 30.

A rod for the 120 mm calibre is around 700 mm long with a corresponding diameter of some 23 mm (root diameter of the load transfer thread). Compared to the intricate design of a 1960 APDS projectile today's KE penetrators have simple layouts. It is essentially a cylindrical heavy metal rod with a tapered front end (ca. 15° taper angle) with a steel tip and a thread at the rear end for attaching the fin.

The acceleration loads are transferred by the sabot (usually 3 petals) via a long thread. The drawback of this simple design is the very high sabot mass to rod mass ratio. On big calibre rounds the sabot mass amounts to at least 60% of the flying mass even for a clever layout. This fact implies a poor propellant energy utilisation.

Moreover the discarding sabot sections endanger a wide area both in front of the tank and laterally. Therefore it is clear how to increase KE projectile performance:

- reduce sabot mass significantly
- maximise penetrator length within the system boundary with no projectile muzzle velocity loss

Sabot technology has practically been stagnant for the past 30 years. Sabots still consist of the same high-strength aluminum. In the USA tests with big calibre fibre composite sabots seem to have been successful. The aim of reducing sabot mass was missed however, the proportion still being 60%, possibly because of the DU-penetrator. Practicable ways to increase penetration performance have been demonstrated in [4].

Heavy metal rods having aspect ratios in excess of 30 tend to bending deformations after sabot separation and to breaking up in spaced armour. The cure is to step "back to the future" to the begin of KE projectile development and use a stiffening jacket again: Both launch ballistics (bending vibrations) and terminal ballistics (break-up in spaced targets) call for an appropriate cross-section (moment of inertia) as a function of rod length.

Jacketing the rods allow aspect ratios of 40 and higher ("inner" aspect ratio). The jacket material should have a low density and a high modulus of elasticity (Young's modulus). For optimum design the bending stiffness (modulus x moment of inertia) of the jacket should equal core bending stiffness, see [4]. For steel jackets and tungsten cores the ratio of outer to core diameter turns out to be 1.28.

Jacketed penetrators are being investigated in several places, using various jacket materials [4, 5, 6]. Results of steel jackets are readily available, partly of fibre composite and titanium jackets as well [7].

A jacketed penetrator becomes considerably lighter for a given outer diameter and therefore faster (but with slightly higher drag). It is now possible to extend penetrator length to the system boundaries. However the blemish is now the sabot dead weight relation increase to more than 70% of the flying mass. The application of more advanced sabot technology is therefore prerequisite. According to the boffins a 30% mass reduction at reasonable cost should well be feasible. At the same time the muzzle velocity would increase again.

A typical future penetrator would compare to the state of the art tungsten rod of 30 aspect ratio as follows:

around 15% longer
nearly 8% faster
yielding ca. 22% higher penetration

i.e. a penetration increase of about 150 mm (Fig. 4), up to 825 mm RHA, i.e. nearly 7 calibers (refered to 120 mm).

The main feature of such a jacketed penetrator is its very low break-up probability in complex targets. Moreover the steel jackets induce favourable flow dynamics in the target material resulting in impact craters of lower cross-sections, similar to DU penetrators. Thus the lower mean density of the jacketed penetrator will at least be compensated, as shown in Fig. 5. The numerous results prove the fact that both monoblock and jacketed projectiles reach the same penetration for the same rod length and the same velocity.

Remark: We have committed ourselves to one specific trend. Different ideas can certainly be found in the proceedings of this symposium. Critical comparisons are left to the readers.

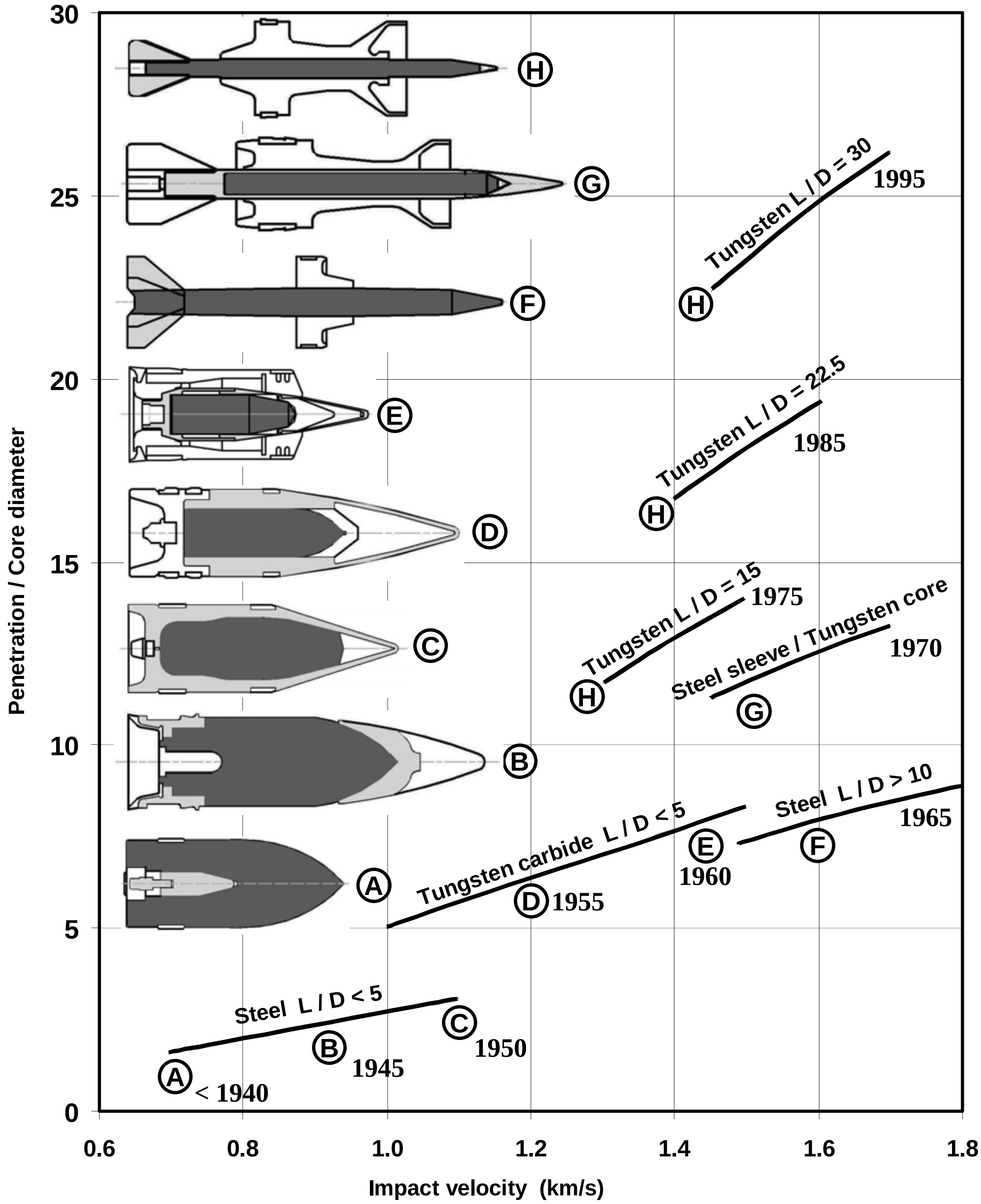

FIGURE 3. KE-projectiles: Development and penetration milestones in RHA (BHN 260 / 0° NATO-obliquity)

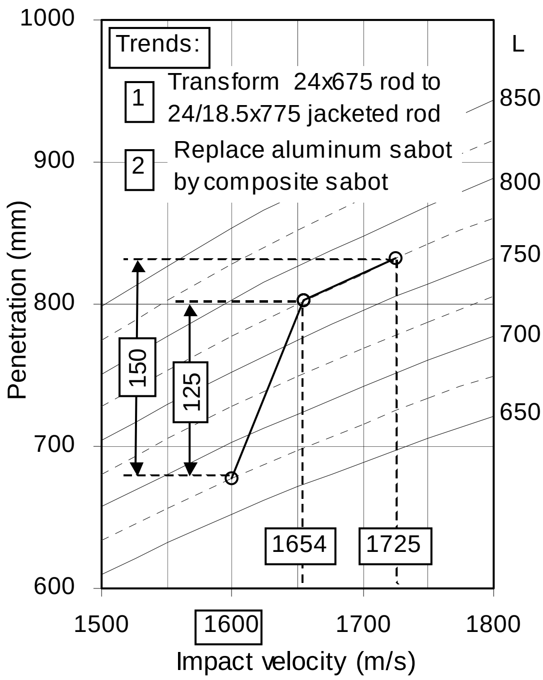

FIGURE 4. Penetration in RHA (BHN 260 / 60°)

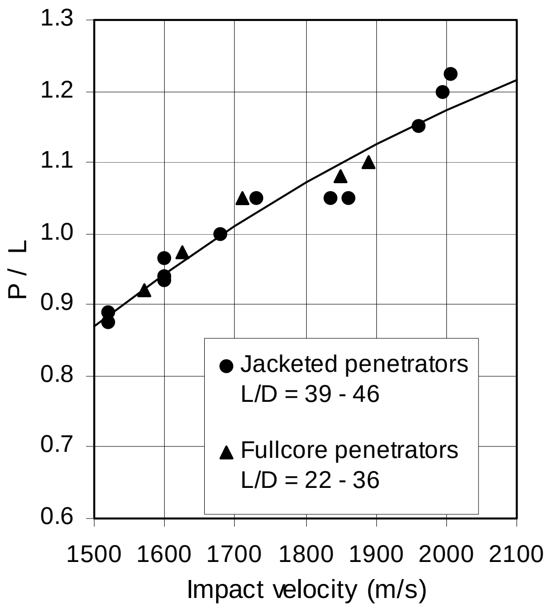

FIGURE 5. Comparison of big caliber fullcore and steel-jacketed tungsten penetrators in oblique RHA-plates (BHN 260)

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