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# EXPERIMENTS WITH JACKETED RODS OF HIGH FINENESS RATIO

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**Summary**—Cylinders of high fineness ratio can show severe integrity and stability problems during acceleration and free-flight phase. The paper describes a method to overcome these problems by adding an envelope to the slender cylinder thereby augmenting the stiffness under flexure. Theoretical considerations treat the pros and cons of jackets with different Young's moduli while looking at various parameters such as maximal deflection, total mass as well as muzzle and impact velocity.

Special emphasis is given to the terminal ballistic efficiency which has been tested using jacketed model penetrators made of tungsten heavy metal with carbon-fibre reinforced plastic (CFRP) and steel envelopes. Some experiments were carried out with cannon-launched CFRP-jacketed tungsten rods of aspect ratios from 45 to 60 being accelerated up to 2000 m/s. In other penetration tests L/D=25 and 40 jacketed penetrators were shot onto homogeneous semi-infinite RHA targets and also spaced targets at 60° incidence at velocities up to 2500 m/s by aid of a light-gas gun.

The experiments with jacketed model penetrators of 3 and 4 mm diameter at high impact velocities showed a good penetration power into homogeneous targets, whereas there is a loss of penetration efficiency into spaced targets of 20% and more. Furthermore it seems that the relative thickness of the jacket should not exceed a certain value in order not to risk a detrimental effect on the penetration performance.

## INTRODUCTION

In regard of modern accelerators such as electromagnetic or light-gas guns as well as RAM launchers and with the demand of a steadily increasing perforation power a number of different hypervelocity projectiles with quite interesting penetrators are being discussed, the number of which is furthermore increased by the need to defeat different target types **[1,2,3,4]**. Nevertheless it can be assumed that for the near future a classical but enhanced powder gun as an accelerator and a sophisticated kinetic energy long rod penetrator will meet the demands at least in the lower section of the hypervelocity impact field, whereas projectiles with other penetrator types such as tandem or segmented rods being shot from most modern accelerators might be the choice in the upper velocity level.

Looking at homogeneous rod penetrators the most important parameters ruling penetration power are density and length of the projectile as well as striking velocity at the target. Now, modern penetrator materials do already have a very high density that can scarcely be increased furthermore; on the other hand, in order to achieve high muzzle velocities it is necessary to get low launch package masses. For a penetrator with great length this results in relatively small diameters and hence high fineness ratios **[5,6]**.

The paper shows some difficulties that arise when accelerating projectiles of high fineness ratio and also presents a simple method how to overcome these stability and integrity problems by supporting the thin and flexible rods by a jacket of appropriate material. Of great interest is of course the effect of this additional hull on the penetration performance of the jacketed rods. Model experiments were carried out with several penetrator types with aspect ratios of 25 and 62 striking at velocities in the range from 2000 m/s up to 2500 m/s.

## REMARKS ON THE CONCEPTION OF JACKETED CYLINDERS

It is obvious, that the great length of these projectiles can lead to several integrity problems such as bending and buckling or even fracture of the projectile tip and/or rupture of the projectile rear section during acceleration in the gun tube as well as to bending vibrations during the free-flight phase. These deformations and oscillations are generated during the inbore travel of the projectile and are carried on in the free flight phase. Model-scale experiments with sub-calibre homogeneous projectiles made of tungsten heavy metal (WHM) with an aspect ratio of 40 clearly demonstrate these effects. As an example of such

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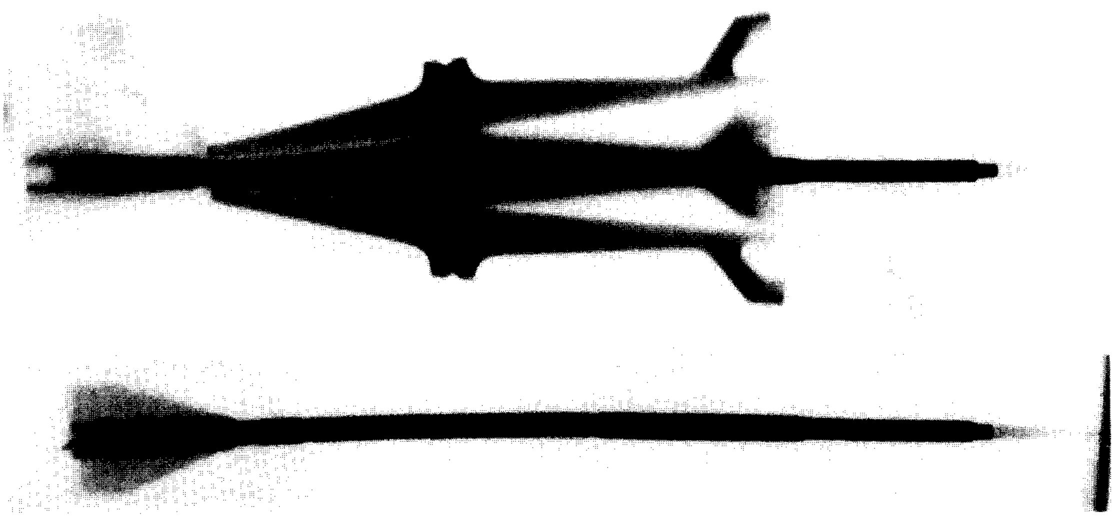

Fig.1. X-ray photographs of projectile in flight (D=6 mm, L/D=40) at 1710 m/s, 1,5 m (above) and 20 m (below) from the muzzle

an experiment a flexure of a 6 mm penetrator at a distance of about 20 m off the muzzle is clearly apparent in **Fig.1** (**[7,8]**). From other experiments also fracture of projectile sections or rupture of the end section has been noticed, so that it seems necessary to support the slender rods as soon as they exceed a certain relative length.

In order to maintain structural integrity of the projectile during acceleration and free flight we suggested to add an envelope to the slender cylinder thereby augmenting the stiffness under flexure. Let us shortly check the pros and cons of such a jacket which for the first exchange of ideas and to simplify matters is taken to be of circular cross section, thereby forming an additional tube around the rod.

Looking at maximal stiffness, acceleration forces and muzzle velocity the best choice would be a material of high Young's modulus and low density. Then in terms of drag, projectile velocity at the target and penetration capability only a reduced performance can be expected.

As an example we take a rod of 25 mm diameter and 600 mm length. The outer diameter of the rod, respectively the jacket remains unchanged and we compare the homogeneous rod with the jacketed rods of a 15 mm inner diameter. The penetrators are subjected to a uniformly distributed lateral load along their axis, being proportional to acceleration and unit mass.

These assumptions allow us to calculate some interesting data for various rod configurations such as homogeneous rods with a diameter of 25 mm (and also 15 mm for comparison) and jacketed rods (15 mm) with envelopes of different modulus of elasticity. These parameters are maximal deflections and bending stresses as well as some more specific munition parameters such as total mass, muzzle and impact velocity. For these calculations the rods are taken to be accelerated by the same propulsion system which means constant muzzle energy for the total launch package. In order to evaluate the terminal ballistic efficiency of these penetrators we planned to perform several test series.

Some data of possible concepts are summarised in **Table 1**. Looking at the homogeneous penetrator with a diameter of 15 and L/D=40, it is evident to find the highest deflections and bending stresses, and because of the low mass muzzle and target velocities are also very high. The maximal deflections are of course reduced by any jacket material, but this effect is more evident the higher we choose the modulus of elasticity. But even with a Young's modulus of about 79% of the penetrator material (case D) we can reduce the maximal deflection to some 20%. This is only about half the value of the homogeneous 25 mm rod having a higher modulus and obviously also higher mass.

/ a72_Tab1.xls /

| | A | B | C | D | E |
|---|---|---|---|---|---|
| rod | homog. | homog. | jacketed | jacketed | jacketed |
| D/mm | 15 | 25 | 15-25 | 15-25 | 15-25 |
| L/D | 40 | 24 | 40 | 40 | 40 |
| | | | | | |
| RELATIVE VALUES : | | | | | |
| density (jacket) | 0 | 0 | 0,240 | 0,091 | 0,254 |
| | | | | | |
| Young's modulus (jacket) | 0 | 0 | 0,329 | 0,786 | 1,429 |
| | | | | | |
| maximal deflection | 1,000 | 0,360 | 0,445 | 0,185 | 0,137 |
| | | | | | |
| < jacket | 0 | 0 | 0,244 | 0,243 | 0,326 |
| max. bending stress < | | | | | |
| < core | 1,000 | 0,600 | 0,445 | 0,185 | 0,137 |
| | | | | | |
| total mass | 1,000 | 2,780 | 1,427 | 1,162 | 1,453 |
| | | | | | |
| velocity at muzzle | 1,000 | 0,865 | 0,962 | 0,982 | 0,960 |
| | | | | | |
| velocity at target (2 km) | 0,906 | 0,817 | 0,843 | 0,837 | 0,843 |

Table 1: Relative data for homogeneous and jacketed rods of identical shape (25 mm outer diameter, 600 mm length) being accelerated by the same propulsion system. Data referring to case A (homogeneous rod, D=15 mm)

As to the bending stresses they are reduced by 40% when the 25 mm rod is used instead of the 15 mm cylinder. A significant reduction can be attained if a jacket is used as shown in case C, but the main load is still carried by the core. Only in the case of a very stiff hull this component takes a significant part of the bending stresses. This is true with about equally distributed loads (case D with 19% maximal bending stress in the core) and even more if the hull's modulus of elasticity is higher than the one of the core (case E). Then the bending stress in the penetrator is reduced to 14% of the initial value, hence the stresses in the core are very much reduced and the hull takes 2/3 of the total load.

The variable masses of the penetrators result in different muzzle velocities. Of course the 15 mm homogeneous penetrator – if it is possible to accelerate this projectile of very high aspect ratio – reaches the highest velocity at the muzzle and at the target as well. All other variants show lower velocities, but it is interesting to note that for the target distance chosen the impact velocities of all jacketed projectiles are still slightly higher than for the 25 mm homogeneous projectile.

From these data it might be said that in terms of maximal deflection and bending stress these jackets could help to solve the problem; as far as impact velocity is concerned there is not necessarily a detrimental effect if a light but stiff hull is used to support a penetrator of a very high fineness ratio.

## TERMINAL BALLISTIC EXPERIMENTS

In order to test the terminal ballistic efficiency several series of experiments were carried out with model penetrators. First, to principally prove the performance of the concept in terms of structural integrity of the projectile during acceleration and free flight as well as the impact efficiency, tungsten heavy metal test penetrators were chosen with a length of 180 mm and a diameter of 3 and 4 mm, respectively.

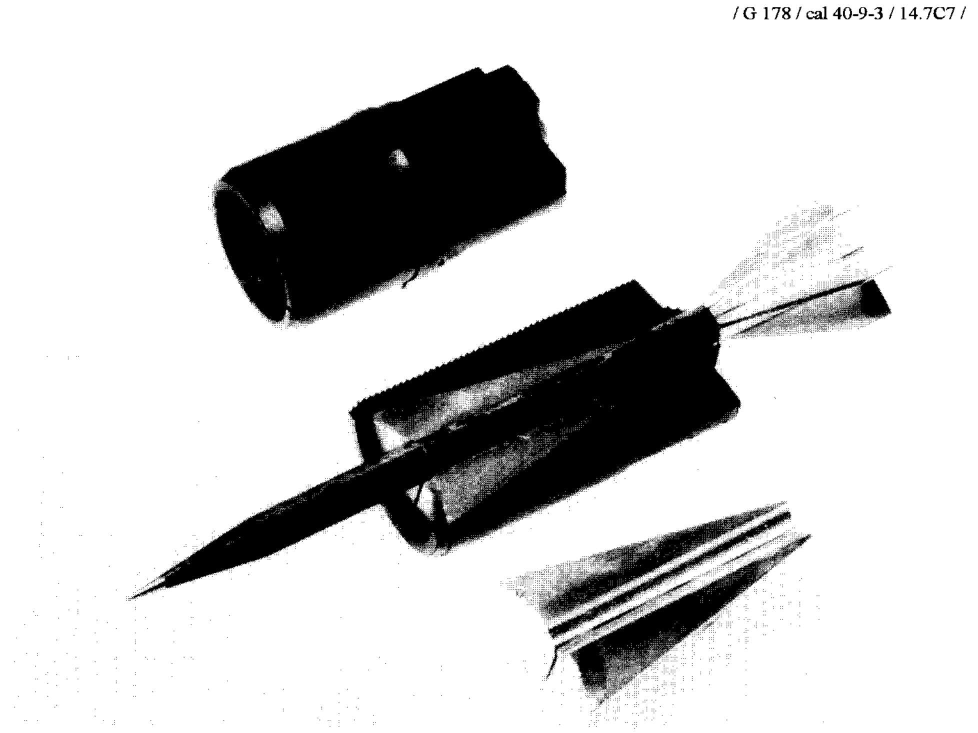


Fig.2. Fin-stabilised jacketed projectile with friction sabot; projectile: WHM-core, D=3 mm, L/D=62, CFRP-jacket; sabot: aluminium and CFRP

The hull was made of carbon-fibre reinforced plastic with orientation of the fibres parallel to the rod's axis. **Fig.2** shows some parts of the launch package, i.e. the jacketed projectile together with a special construction of a friction sabot **[9]** consisting of 8 elements as it was accelerated in a 40 mm experimental powder gun. Penetration depths were measured in a stack of RHA plates of 52 mm thickness being looked at as a semi-infinite target.

As an example **Fig.3** proves the feasibility of the concept of a jacketed WHM-projectile with an aspect ratio of 62 being accelerated with about 130 kG's to a velocity of 2020 m/s. The X-ray photograph does only show the penetrator (3 mm diameter) and not the CFRP-hull, the external diameter of which was 9 and 8 mm, respectively, in the zone of sabot contact. The rear part of the projectile near the stabilisation fins gives an idea of the real proportions.

The following two figures show the craters formed by the impact of these projectiles. The crater in **Fig.4** was formed by a penetrator of 4 mm diameter and an L/D-ratio equal to 46 impacting at 1937 m/s with less than $1^{o}$ incidence. The crater with a diameter of about 8 mm is very likely to be formed mainly by the penetrator material with only little contribution from the jacket, so that the tulip-formed mouth of the crater is certainly due to the hull material which is taken to be scraped off the core at that point. The crater depth into the stack of 4 RHA plates is equivalent to an efficiency of 0,9 compared to a value of about 1,1 for a corresponding homogeneous penetrator with identical aspect ratio and impact velocity.

Another crater formed by an impact of a jacketed penetrator with D=3 mm and L/D=62 at a velocity of 2020 m/s is shown in **Fig.5**. Although the photograph of the flying projectile does not show any anomaly (compare Fig.3) it is evident from the crater shape that the projectile impacted in several fragments.

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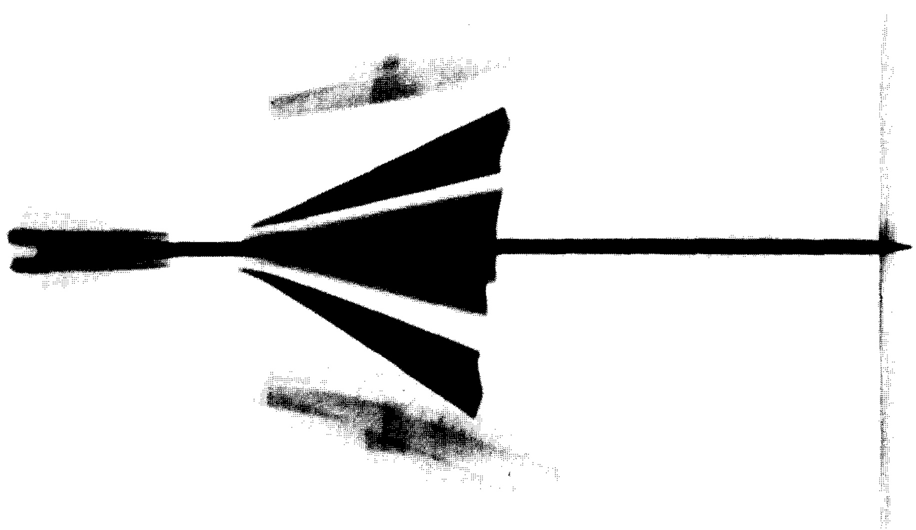

Fig.3. Jacketed penetrator in flight with separating sabot petals (L/D=62; v=2020 m/s)

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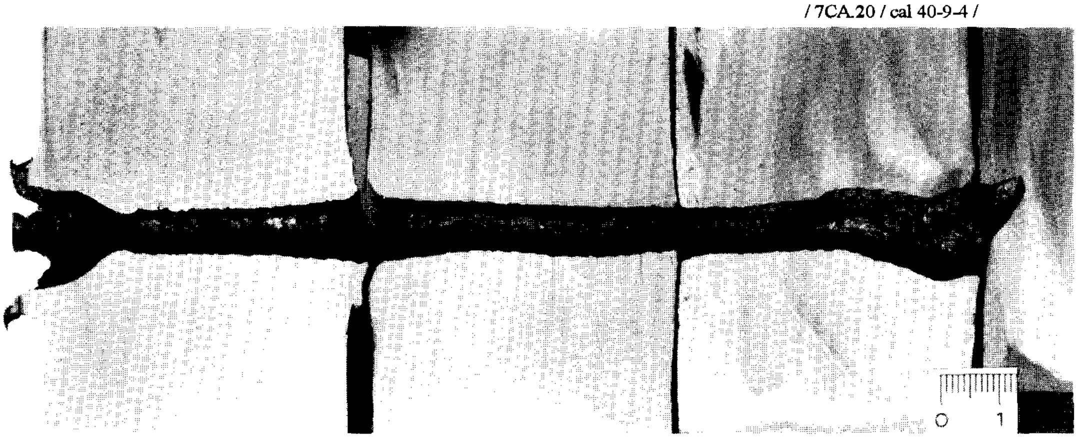


Fig.4. Crater formed by a jacketed rod with CFRP-hull (D=4 mm, L/D=46, v=1937 m/s)

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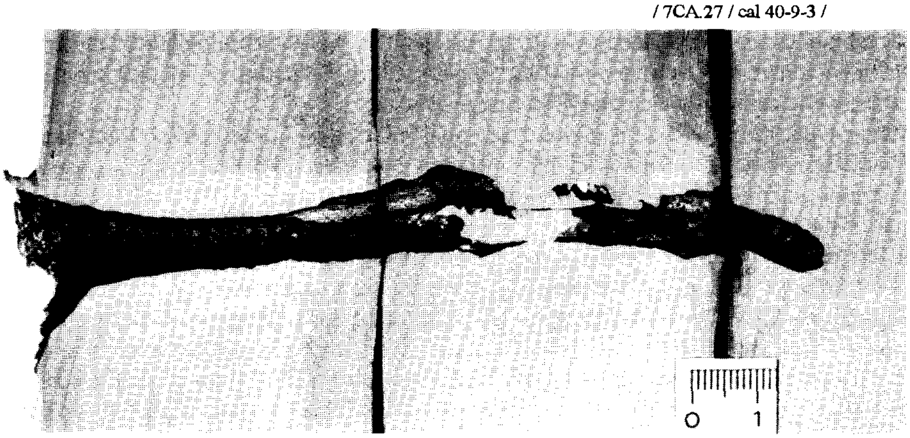


Fig.5. Crater formed by a jacketed rod with CFRP-hull (D=3 mm, L/D=62, v=2020 m/s)

We do find indications for hydrodynamic penetration and we do also find direct prints of the core diameter in the deeper part of the crater.

Regarding the crater form and the materials involved it can be assumed that with respect to the hull's significant lower density the penetration velocity is much less than that of the core made of tungsten alloy. This produces two coaxial craters with different crater ground velocities and diameters. The narrow and rapidly moving crater of the core is followed by the wide and slowly increasing crater of the hull. It can be assumed that the penetrating parts of the rod which have already passed the crater formed by the hull are loaded by tension caused by friction effects from the outer material. Also adhesive forces between hull and core must be taken into consideration. In addition, the succeeding rod material is compressed and tends to bend or buckle. The projectile fails by fracture if the stress exceeds the strength of the core material. These separated fragments collide with the crater wall or even with proceeding rod parts. In the following they are either deflected or penetrating the cavity out of the given line of sight. Thereby the projectile energy dissipates and the efficiency of the rod decreases below 2/3.

Further experiments with higher impact velocities were performed by the aid of a light gas gun. In order to reduce the sensitivity of the projectiles against axial loading while accelerating them with pusher-plate sabots the length of the penetrator was limited to 120 mm. The diameter of the projectile and the outer diameter of the hull remained unchanged. The target arrangement was again a stack of plates made of RHA. At impact velocities between 2300 m/s and 2500 m/s the penetrators achieved efficiencies of about 1,25. As an example the following picture shows a crater profile with a tulip-formed transient area at the beginning of the penetration (**Fig.6**), which is caused by the erosion of the hull as already described.

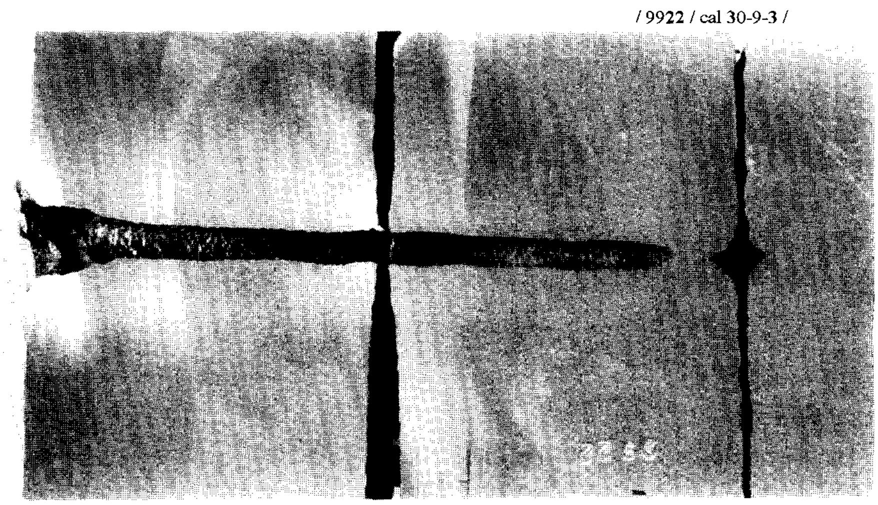


Fig.6. Crater formed by a jacketed rod with CFRP-hull (D=3 mm, L=120 mm, v=2340 m/s)

The crater continues as an extended cylindrical cavity. The diameter and depth of the crater implies that the rod has penetrated relatively undisturbed. Looking at this experiment the hull seems to be separated from the penetrator without causing any fracture processes.

If that is true, the reference penetrator of equal mass, length and velocity must achieve nearly the same performance.(Remark: This is slightly different from the reference condition used in **[10]**.) **Fig.7** shows the crater profile of such a reference experiment. At an impact velocity of 2400 m/s the normalised penetration of the homogeneous projectile was found to be 1,28. Thereby the efficiency of the two penetrators differs only in the order of 2%. Although the CFRP hull contributes with a mass fraction of more than 40% to the total mass of the jacketed projectile, the main advantage can only be seen in achieving a structural integrity during acceleration and flight, whereas a positive contribution to the terminal ballistic performance is hardly possible. With respect to its relatively low penetration velocity such a thick-walled hull of low density material has an extremely high erosion rate. For 1 cm of crater depth the hull loses nearly its entire length. The deformed and rejected hull material cannot be stored in the crater volume which is produced by the proceeding core. Therefore it will be separated from the penetrator at the very beginning of the penetration process. From these experiments at normal incidence it might be suggested that this separation process takes place without fracture of the penetrator at lower aspect ratios, whereas we found detrimental effects at higher L/D numbers caused by the friction forces mentioned above.

Further tests were performed in order to check the penetration capability of jacketed rods against inclined spaced targets. In the case of oblique penetration and hence transmission of lateral load to the rod, the asymmetric tension and flexion forces act at the same time. Under such a mixed load the strain in the penetrator exceeds the plastic limit and the material fails by fracture.

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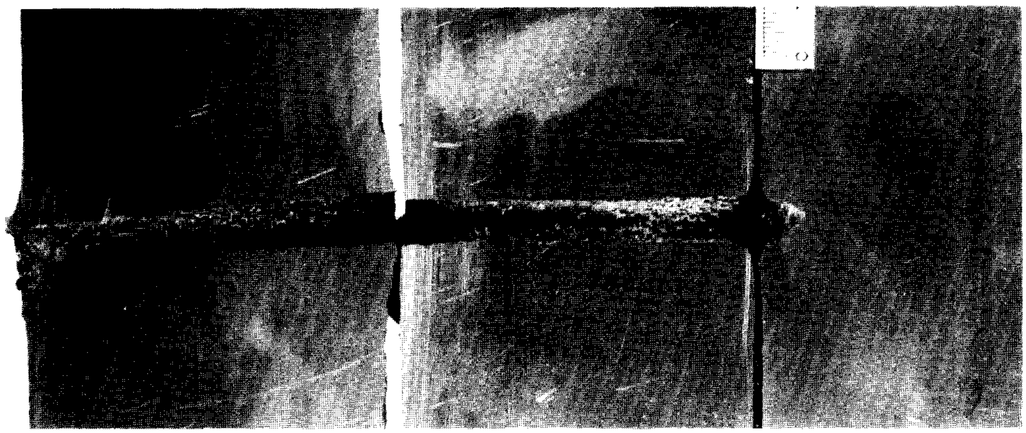

Fig.7. Crater formed by a homogeneous rod (reference experiment) (D=4 mm, L=120 mm, v=2420 m/s)

Such an example is demonstrated in the X-ray picture of **Fig.8** showing the jacketed rod described above during the perforation of a two-plate target. Obviously the plastic strain induced during the penetration of the first plate is high enough to cause fracture processes in the material of the rod.

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Fig.8. CFRP-jacketed rod projectile, two-plate target (D=3 mm, L=120 mm, v=1995 m/s)

Other tests were carried out with four-plate targets under 60° obliquity. As to thicknesses and strengths, the single target plates are arranged as follows: 1x5 mm of 1200 N/mm², 2x9 mm of 500 N/mm² and 1x5 mm of 1400 N/mm². Looking in line of sight there was a distance of 100 mm between each other plate. The residual penetration power was measured in a steel plate (900 N/mm²) at normal impact. As a result of these tests we find that the reference penetrator (D=4 mm, L=120 mm, v=2451 m/s) showed a relative penetration of 0,96, whereas the very sensitive jacketed penetrator (D=3 mm, L=120 mm, v=2386 m/s) did only reach an efficiency of 0,5.

These results confirm once again that – as it could be expected – the relatively thick jackets are not very useful to the extremely slender core of the projectile as far as penetration of oblique targets is concerned. In order to minimise the disturbances and forces transmitted to the penetrator at high obliquity the jacket should not be scraped off. This yields for relative small wall thicknesses of the hull.

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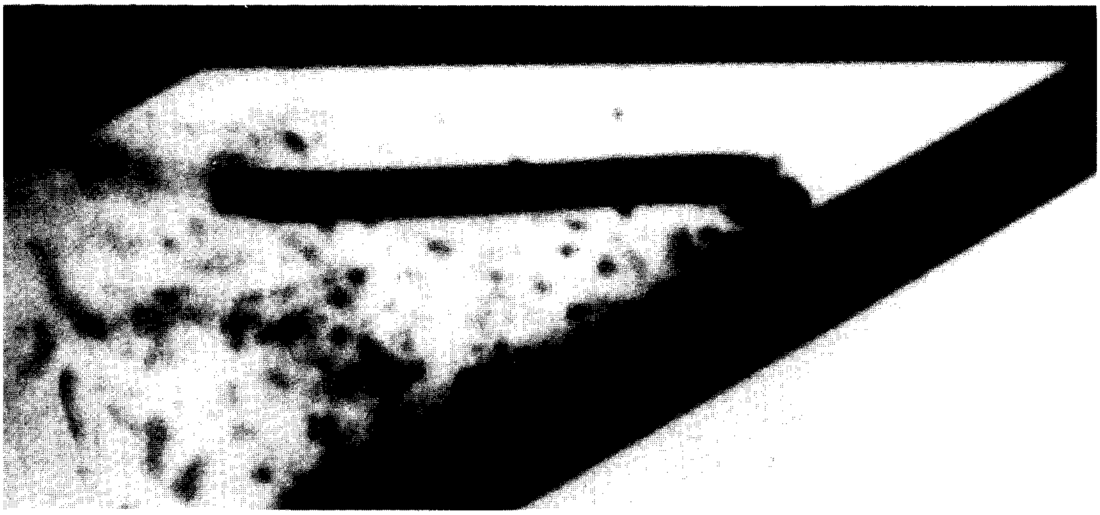

Fig.9. Steel-jacketed rod projectile, four-plate target (D=4 mm, L=100 mm, v=2100 m/s)

Consequently the following experiments were performed with steel-jacketed penetrators in order to check this assumption. For reasons of availability these tests could only be performed with penetrator lengths of 100 mm. The wall thickness of the steel tubes (900 N/mm²) varied from 0,25 mm to 1 mm. Normal impact into a stack of RHA steel plates at velocities about 2100 m/s resulted in efficiencies between 1,2 and 1,26. In these tests no correlation between hull thickness and efficiency could be found. With the corresponding reference projectiles of same mass and length no better values could be achieved.

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Fig.10. Homogeneous rod, four plate target (reference experiment)
(D=4 mm, L=100 mm, v=2077 m/s)

Regarding these corresponding efficiencies it seemed especially interesting to examine the performance of the jacketed projectiles against a structured target. It was found that relative penetration values of the steel-jacketed penetrators into the above mentioned quadruple plate target were no better than 0,8. The following **Fig.9** shows the penetrator between the third and fourth plate of the target arrangement. Looking at the tip portion of the penetrator it is clearly visible that the steel hull keeps in contact with the core and is not slipped off as in case of the CFRP hull.

The efficiency of the homogeneous WHA reference projectile comes up to a value of about 1,0 against this quadruple target. The corresponding **Fig.10** demonstrates the material behaviour of the rod while penetrating this target. Despite the differences in the efficiencies attained in experiment, there is no appreciable disadvantage apparent in comparison between the Fig.9 and Fig.10 as far as the jacketed penetrator is concerned. Therefore it can be assumed that the penetrators with additional steel hulls are relatively insensitive to the loads emanating from the perforation of an inclined multiplate target. Obviously the crater formed while penetrating into homogeneous as well as spaced targets is big enough to hold the erosion products of both penetrator and hull. At least there is no indication of friction or fracture processes as observed in case of the CFRP jackets. This can be due to the higher hull density and higher penetration velocity and most probably to the relative hull thickness being better adapted to the diameter of the penetrator.

## FINAL REMARKS

It could be demonstrated by the model experiments that the cladding of cylinders is a good means to maintain structural integrity during acceleration and free flight of KE rods with high fineness ratio . On the other hand it is not evident that the jacket is also of benefit to the terminal ballistic performance: as far as the stiffness is concerned, section area and Young's modulus are of importance, whereas in this respect the ruling parameters for penetration are density, strength and hull thickness **[11]**.

In comparison to a homogeneous penetrator, the jacketed penetrator of the same outer diameter shows only about 40% of maximal deflection and strikes the target with a velocity which is even 3% higher (comp. Table 1). The penetration performance of the jacketed rod is strongly depending on the target type. In the case of homogeneous target at normal incidence there is about the same penetration depth. If thick walled low density hulls are used, there is a loss in performance up to 50% when penetrating spaced targets. More dense jackets of smaller wall thickness reduce these losses to about 20%. In fact the hull masses added to the actual penetrator did never show an own contribution to the total penetration. In terms of terminal ballistics the hull can therefore be looked at as a parasitic mass (comp. **[10]**, Fig.5).

Needless to say – and this has been proved in quite a lot of experiments – that the high fineness ratio penetrators, jacketed or not, are extremely sensitive to yawed penetration (see **[12]**). At hypervelocity impact with increasing crater diameters this feature might be less detrimental, which demonstrates once again the influence of hull thickness. Nevertheless jacketed penetrators offer the possibility to accelerate penetrators of a much higher fineness ratio as it would be possible with a homogeneous concept.

## REFERENCES


1. BRISSENDEN; C., Performance of novel KE penetrator designs over the velocity range 1600 to 2000 m/s. *Proc. 13th Intern. Symp. on Ballistics*, TB-27, Stockholm (1992).
2. NAZ, P., LEHR, H.F., The crater formation due to segmented rod penetrators. *Int.J.Impact Engng.*, **10**(1-4), 413-425 (1990), *(Proc. of the 1989 HVIS Symp.)*.
3. ORPHAL, D.L. et al., Impact and penetration by L/D<1 projectiles. *Int.J.Impact Engng.*, **14**(1-4), 551-560 (1993), *(Proc. of the 1992 HVIS Symp.)*.
4. LEHR, H.F., MERKEL, Th.,Computational study on the application of tandem projectiles in different distances of engagement. *Proc. 13th Intern. Symp. on Ballistics*, EB-16, Stockholm (1992).
5. WOLLMANN, E., WEIHRAUCH, G., *ISL-Bericht S-RT 909/90* (1990).
6. LEHR, H.F., Aufbau von Wuchtmunition. *ISL-Bericht CO 224/82* (1982).
7. SCHIRM, V., PAULUS, G., Development of KE penetrators of high fineness ratio. *ISL-Bericht CO 244/90* (1990).

8. LEHR, H.F., Bemerkungen zur Projektil- und Treibspiegeltechnologie. *ISL-Bericht CO 246/90* (1990).
9. WIESE, U., LEHR, H.F., SCHIRM, V.,- GUTH, P., Untersuchungen zur Treibspiegel-technologie: Treibring in Kompositbauweise für Pfeilgeschosse mit Form- und Reibschluß. *ISL-Bericht RT 504/88* (1988).
10. CULLIS, I.G., LYNCH, N.J., Hydrocode and experimental analysis of scale size jacketed KE projectiles. *Proc.14th Intern. Symp. on Ballistics,* TB-7, Quebec (1993).
11. WOLLMANN, E., WEIHRAUCH, G., WELLIGE, B., *ISL-Bericht S-RT 919/90* (1990).
12. BJERKE, T.W., SILSBY, G.F., SCHEFFLER, D.R., MUDD, R.M., High yaw penetration of long rod penetrators. *Proc.13th Intern. Symp. on Ballistics*, TB-28, Stockholm (1992).