Army Research Laboratory

An Overview of Novel Penetrator Technology

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ARL-TR-2395 February 2001

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-TR-2395 **February 2001**

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Abstract

Over the past 25 years, long-rod penetrators have proven to be highly effective when used as a lethal mechanisms in tank-fired ammunition. However, constraints imposed by currently fielded gun systems and the possibility of future, high-velocity gun systems have prompted researchers to examine other penetrator concepts. The rationale for some of these concepts can be found in physical principles embodied in simple one-dimensional semiempirical penetration models. In other cases, certain vulnerabilities of advanced armors can be attacked with novel concepts. In any event, it has been found that departure from a simple, long-rod has posed engineering and fabrication problems that make implementation of the concepts at full scale a major technical challenge.

Acknowledgments

The author would like to thank Dr. Steven Segletes for his helpful comments and careful review of this report. Also, Konrad Frank is acknowledged for the many helpful discussions and technical advice he has provided over the past 20 years.

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1. Introduction

The history of kinetic energy penetrators fired from large-caliber guns goes all the way from cannon balls to the modern saboted long rods made of high-density metal. Changes in penetrator technology have occurred primarily in response to increasing protection levels of armored vehicles, since the modern battle tank is considered one of the primary means for defeating enemy armor. Armor technology has improved to meet the threat of larger gun sizes and higher muzzle velocities. The continual competition between armor and anti-armor technology has led to the adage that (1) given a penetrator, one can design an armor to defeat it, and (2) given an armor, one can design a penetrator to defeat it. However, if increasing gun size is not a viable option, long-rod penetrator designs have a limit; at some point, new concepts must be developed to overcome the advances made in armor technology. This report presents an overview of explored concepts and explains on what penetration mechanics principles they have their basis.

For discussion purposes, novel penetrator designs are those that deviate significantly from a simple right circular cylinder. Right circular cylinders are often fired in laboratory experiments, but they are generally not used in actual ammunition. Figure 1 shows a cut-away drawing of the M829A1 projectile fired from the M256 cannon on the M1A2 main battle tank. The penetrator in the M829A1 closely resembles a right circular cylinder, but engineering considerations have altered the shape somewhat.

Figure 1 also shows the sabot, obturator (seal), nose tip, and fins. The sabot carries the subprojectile down the gun tube and is discarded shortly after muzzle exit. The fins give flight stability, and the nose reduces aerodynamic drag. The propelling charge is not shown here. The process of delivering the penetrator to the target at high velocity involves a large, complicated gun system, starting with target acquisition and continuing with loading the round, aiming the gun, launching the round, flying it, and finally impacting the target. The ultimate success of a novel penetrator concept depends not only on its terminal ballistic performance, but also on how well it is integrated into the existing gun system.

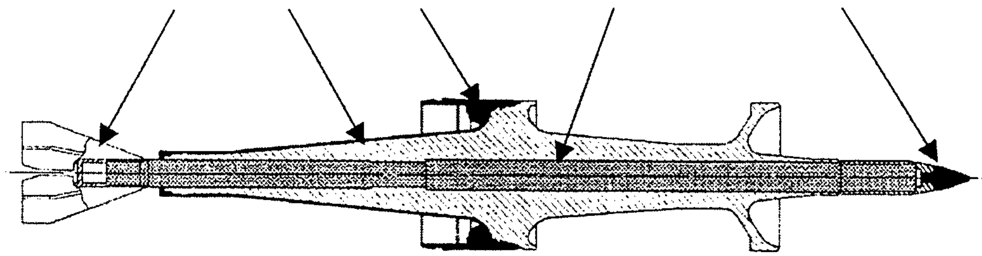


Figure 1. Schematic of the M829A1 Projectile.

A penetrator may also be considered novel if it is made of a material which has unusual penetrating characteristics. This is discussed in more detail in the section dealing with differences between the penetrating characteristics of depleted uranium and tungsten heavy alloys. Excluded from this discussion on novel penetrators are those concepts that require a significant modification of the existing gun system for their effectiveness. In particular, projectile concepts that use a high dive angle toward the armored vehicle to overcome the armor's high obliquity are not considered, even though this can be a very effective approach for the defeat of the armor.

Insight can be gained on the design of novel penetrators by considering the important parameters involved with the penetration process—this is done in the next section. Examples of novel penetrators and their rationale are provided in sections 3–8. The final section provides a summary and recommendations for future research.

2. Penetration Mechanics Principles

Most of the basic analytic models of penetration mechanics are one-dimensional representations of rods impacting a single material. Laminate or layered targets are sometimes addressed by a piece-wise application of the model to each material layer. While this poses some complications, the approach proves to be fairly successful. The advantage of these simple models, as opposed to complicated, three-dimensional computer simulations of terminal events, is that the relevant characteristics of the penetrator are readily apparent. These characteristics should be important for both conventional rods and novel penetrator concepts.

One-dimensional modeling of the penetration process was carried out independently by both Alekseevskii (1966) and Tate (1967), who are credited with including the effects of target resistance and penetrator strength in formulating penetration equations. Wright and Frank (1988) helped to quantitatively describe the makeup of the target resistance. Using the formulation of Christman and Gehring (1966), Frank and Zook (1991) were able to reproduce the experimentally observed effect of length-to-diameter ratio (L/D). Later work by Walker and Anderson (1995) included transient effects in their formulation. More recently, Segletes and Walters (1999) solved the momentum equation in a noninertial reference frame, thus simplifying the mathematical solution obtained earlier by Walker and Anderson (1995). All of these approaches are exemplified by mathematical rigor, but tend to be more complicated than is necessary for this simple overview. Consequently, what follows is geared to a simpler,semiempirical approach to models for penetration mechanics.

The first and simplest of the models is the density law. This law, derived from an application of the Bernoulli Equation, relates the penetration depth P to the product of length L of the penetrator and the square root of the ratio of the penetrator and target density, μ:

$$P = L \bullet \sqrt{\mu}. \tag{1}$$

This relation approximates the high velocity behavior of a long rod penetrator and indicates that important characteristics of a penetrator are its length and density.

Equation 1 can be modified to express the velocity dependence of the penetrator. In the discussion to follow, the penetrator striking velocity v is taken as a characteristic of the penetrator. In fact, it is a function of the gun system from which the penetrator is fired. The penetrator is part of that system, so there is some small dependency of the velocity on the other penetrator characteristics such as mass and geometry. However, the velocity is determined primarily by the gun size (muzzle energy), sabot mass efficiency, and distance to target.

From the large amount of available experimental data, it is clear that the penetration vs. velocity follows an S-shaped curve. While there are many mathematical forms that could represent an S-shaped curve, the one form that seems to have gained the most acceptance is the one developed by Lanz and Odermatt (1992),

$$F(v) = \exp(-b/v^2), \tag{2}$$

hereafter referred to as the Odermatt function. Lanz and Odermatt developed an original equation to predict the limit thickness of armor plate being perforated by large-caliber penetrators. The fitting function contained terms in penetrator length-to-diameter ratio, obliquity, and penetrator strength-to-density ratio. For this report, only the velocity dependence is extracted from Lanz and Odermatt's original equation. Here, b is a fitting parameter, and v is the penetrator velocity. The value of F at $v = 0$ is 0, and it approaches 1 as $v \rightarrow \infty$, with a smooth transition between low and high velocity. This form is easy to manipulate mathematically and lends itself to fitting experimental data. The penetration equation then becomes

$$P = L \bullet \sqrt{\mu} \bullet \exp(-b/v^2). \tag{3}$$

More recently, penetration data have been fitted by Rapacki et al. (1995) to the Odermatt function using

$$b = 2S/\rho, \tag{4}$$

where ρ is the penetrator density, and S is related to the target strength through the equation

$$S = q \bullet (BHN)^m. \tag{5}$$

Here, q and m are fitting parameters, and BHN is the Brinnell hardness of the target. At high velocity, Frank (1996) has made certain approximations to show that

$$b \approx (1+\sqrt{\mu}) \bullet (H\text{-}Y)/k\rho, \tag{6}$$

where H is the penetration resistance of the target, Y is the flow stress of the penetrator, and k is a shape/flow factor for the penetrator. However, it should be emphasized that equation 3 has not been derived from first principles and is used mainly as a convenient way to organize and describe penetration data. If a theory were ever produced which gave P as a function of the relevant variables in the form of equation 3, then b might be a very complicated function of target and penetrator strength and density.

It is also known from experimental penetration data that P depends on the length-to-diameter (L/D) ratio of the penetrator. For instance, if one assumes that the penetration hole volume (assumed hemispherical) in the target is proportional to the kinetic energy of a cylindrical projectile with L/D = 1, then

$$P/D = c \bullet \rho^{1/3} \bullet v^{2/3}, \tag{7}$$

where c is a constant involving the rod geometry and the proportionality constant. Equation 7 indicates that penetration depth increases as $v^{2/3}$, whereas equation 3 indicates that the penetration depth levels off with increasing velocity. This contradiction can be dealt with by ascribing the relative steady-state portion of the penetration process for long rods to equation 3, and then identifying the final transient penetration phase (involving approximately one penetrator diameter) to equation 7. A heuristic penetration formula, similar in form to that given by Frank and Zook (1991), that explicitly contains the effects of L/D ratio is then

$$P = L \bullet (1\text{-}D/L) \bullet \sqrt{\mu} \bullet \exp(-b/v^2) + D \bullet c \bullet \rho^{1/3} \bullet v^{2/3}. \tag{8}$$

Including of the second term in equation 8 is a plausible, although not scientifically rigorous, way to include the effect of a second geometric variable. In fact, Anderson et al. (1997) argue that for tungsten penetrators attacking RHA targets in the velocity regime of 1 to 2 km/s, equation 8 does not give an accurate representation of the L/D effect. For high velocities and large L/D ratios, this formula approaches the form of equation 1. For L = D, the formula reduces to equation 7. The formula explicitly contains the important parameters for penetration, with the exception that target and penetrator material properties can be hidden in the fitting parameters b and c. Penetrator mechanical properties (strength, ductility, fracture toughness, etc.) are important during the launch and flight process, but are not so important for normal penetration into monolithic materials. Of course, for attack of oblique, spaced, and reactive armors, mechanical properties and material processing become very important.

As seen in subsequent sections of this report, the rationale for a given penetrator concept is consistent with the penetration mechanics contained in equation 8. Consider the fact, however, that modern main battle tanks are not limited to monolithic, homogeneous, passive armor. Thus, novel penetrator concepts based on physical principles represented by equation 8 may not be as successful as anticipated in defeating advanced armor designs. However, even modern fielded tank armors employ a large, structural element made up of rolled, homogeneous armor in front of which the advanced portions will be placed. What is left of the penetrator after defeating the front portion of the armor has to perforate the final section. The principles represented by equation 8 are useful for this application.

The density law (equation 1) can be used to get a rough idea of the relative importance of penetrator length and density. Suppose one has two long-rod penetrators with the same mass and diameter but different lengths and densities. At high velocity, the ratio of the penetration depths is given by

$$P1/P2 = L1/L2 \bullet \sqrt{(\rho 1/\rho 2)}, \tag{9}$$

where the 1 and the 2 refer to the two different penetrators. Let $L1 > L2$ and $\rho 1 < \rho 2$. Since it is assumed that the rods have the same mass M and diameter D,

$$M = \pi \bullet (D^2)/4 \bullet L1 \bullet \rho 1 = \pi \bullet (D^2)/4 \bullet L2 \bullet \rho 2. \tag{10}$$

Then,

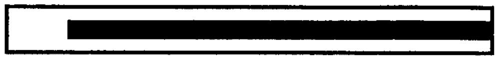
$$P1/P2 = \sqrt{(\rho 2/\rho 1)} > 1. \tag{11}$$

Therefore, for high-velocity long rods, the longer, lower-density rod outperforms the shorter, higher-density rod in terms of penetration depth. As seen in the next two sections, some novel penetrators are simply attempts to rearrange a given penetrator mass into a longer configuration, while the average, effective density decreases to keep the mass constant.

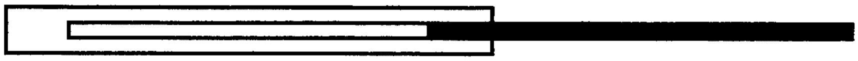
3. Extending Rods

For rod penetrators, equation 8 indicates that the dominant parameters for penetration are penetrator length, density, and velocity. High density is achieved by choosing a high-density metal, usually depleted uranium (DU) or a tungsten alloy (a composite of tungsten particles in a metal matrix). Projectile velocity is a function of the gun system, and it is usually set as high as possible for the given penetrator to be launched. Penetrator length has increased in fielded ammunition over the past two decades, indicating the importance of this parameter in penetrator performance. An important consideration for a projectile designer is how to increase penetrator length on target while remaining inside the constraints imposed on a cartridge that can be fired from a fielded gun system. One answer is the extending rod. The general idea here is to launch a penetrator in a compact state and then extend it in flight, preferably near the target. Note that shaped charges were the original embodiment of this concept.

Perhaps the simplest form of an extending rod is the rod-tube concept shown in Figure 2. The rod-tube is fired from the gun in its compact form (Figure 2a) and then extended in flight (Figure 2b). In most applications, the rod portion of the rod-tube strikes the target first. In addition to the important penetrator characteristics already mentioned, two additional parameters must be considered—tube thickness and the amount of axial overlap between the rod and the tube (extension ratio). This particular novel penetrator concept has been investigated by several research organizations, including Lawrence Livermore National Laboratory (Holt et al. 1990), California



(a) Compact Form



(b) Extended Form

Figure 2. Rod-Tube Penetrator Concept.

Research and Technology (Franzen and Schneidewind 1989), General Research Corporation (Isbell et al. 1995), the U.S. Army Research Laboratory (ARL) (Weinacht and Ferry 1992; and Farrand 1995), and Physical Sciences, Inc. (Lo et al. 1996). The current discussion is limited to unclassified material so that only a small portion of the relevant literature is represented here. Note also that the Security Classification Guide for Kinetic Energy Penetrator Technology, published by ARL, states that detailed descriptions of mechanical devices and techniques that represent practical means of implementing penetrator extension are classified. This restriction further limits the discussion of novel extending penetrator concepts.

Unclassified model-scale terminal ballistics results for a specific rod-tube design have been reported by Lynch et al. (1995). Their design featured a tube with an outer dimension of 10.6 mm (including buttress grooves), an inner dimension of 5 mm, and a length of 46.5 mm. The extended portion of the rod was 40.55 mm, and there was an approximate 5-mm overlap between the rod and tube. This rod-tube design was tested in the deployed configuration, and penetration depths were compared with those achieved against a solid steel target by a unitary rod 46.5 mm long and 10.6 mm in diameter (including buttress groves). For the velocity range examined, the rod-tube penetrator outperformed the unitary penetrator by 31–57%, depending on the impact velocity. Doubling the length of the penetrator with half of it in the form of a tube does not double the penetration depth. These numbers give a favorable performance comparison for the rod-tube concept because the extension ratio is almost as high as it can get. Other results would be obtained for different values of the tube-wall thickness. For a given tube-wall thickness, the overall penetration performance would decrease as the extension ratio decreases.

This comparison also raises the question of which baseline performance should be used. A 30% increase in performance is significant, but viewed in a larger context, how realistic is it to achieve this degree of improvement? Lynch et al. (1995) attempted to answer this question by firing an equal-mass penetrator with a higher L/D ratio than the 10.6-mm-diameter rod. They found that the higher L/D penetrator outperformed the rod-tube concept at all velocities tested. This very simple example demonstrates that it is sometimes possible to achieve a better result without resorting to complicated penetrator configurations. On the other hand, if the cartridge constraint is such that a longer penetrator cannot be used, then an extending rod may be the only answer for improved performance against a thick monolithic target.

Selected data from Lynch et al. (1995) shown in Table 1 suggest that there is an influence of penetrator velocity on the performance of a rod-tube penetrator as compared to that of the baseline penetrator.

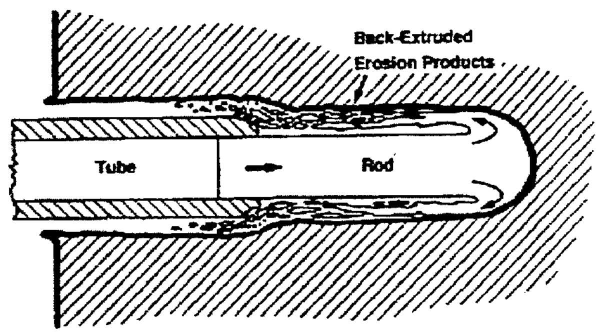
A simple explanation of the effect of velocity is shown in Figure 3. At the lower velocity, the penetration channel made by the leading rod element is barely wide enough to accommodate the trailing tube element. In fact, there might be some interaction of the penetrator back-extruded erosion products and the shoulder formed by the rod-tube connection. At higher velocity, the penetration channel becomes broader and interference is much less likely. The tube thickness plays an important role; the thicker the tube is, the higher the velocity that is needed to expand the initial crater diameter to accommodate the tube. Note also that detrimental yaw effects will be magnified at the lower velocities due to the interaction of the tube and crater wall.

The rod-tube penetrator is a good example of a novel penetrator concept that requires high velocity to achieve its full performance level against thick monolithic targets. The concept was a candidate under consideration for launch by high-velocity electric guns (Andricopoulos 1993). When actual hardware was designed to launch this concept from a conventional powder gun in the

Table 1. Rod-Tube Penetration Data From Lynch et al. (1995)

Penetrator	Impact Velocity (m/s)	Total Yaw (deg)	Penetration (mm)	Percent Increase
Baseline	1,833	NR	63	—
Rod-Tube	1,834	2.2	82.5	31
Baseline	2,621	3.8	77	—
Rod-Tube	2,636	3.4	117.5	52
Baseline	2,919	3.0	78	—
Rod-Tube	2,893	2.2	122.5	57

(a) Low Velocity



(b) High Velocity

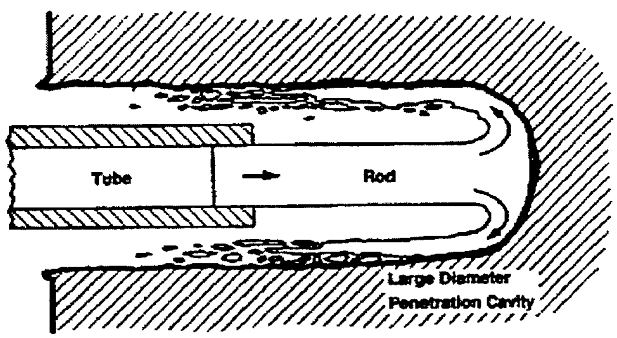


Figure 3. Effect of Velocity on Rod-Tube Performance From Magness and Frank (1993).

early 1990s, two design difficulties had to be overcome. First, the sabot could not grasp the rod directly. This meant that most of the launch forces had to be transferred from the sabot to the tube without interfering with the ability of the rod to extend from the tube. Second, some deployment mechanism had to be devised. The pressure differential between the nose and fins was used to extend the rod from the tube after launch. However, only limited extension was achieved in the early tests, and the concept was later dropped from consideration.

Magness and Frank (1993) suggested a novel penetrator concept that overcame some of the difficulties previously mentioned. Their concept, called a split-rod projectile, is shown schematically in Figure 4; the rod has been sliced diagonally along its length. In the extended form, the new penetrator has a greater length and smaller average diameter. This concept has the advantage that its mass is concentrated around the central axis. Also, there is a gradual change in diameter along its length, avoiding the abrupt shoulder that is characteristic of the rod-tube projectile. Also, the compact rod is configured in such a manner that the sabot is able to grip both halves of the split rod. The design features of the split-rod concept allow it to reach its full performance level at ordnance velocities. However, there are certain aerodynamic problems this concept has to overcome before a practical application is possible.

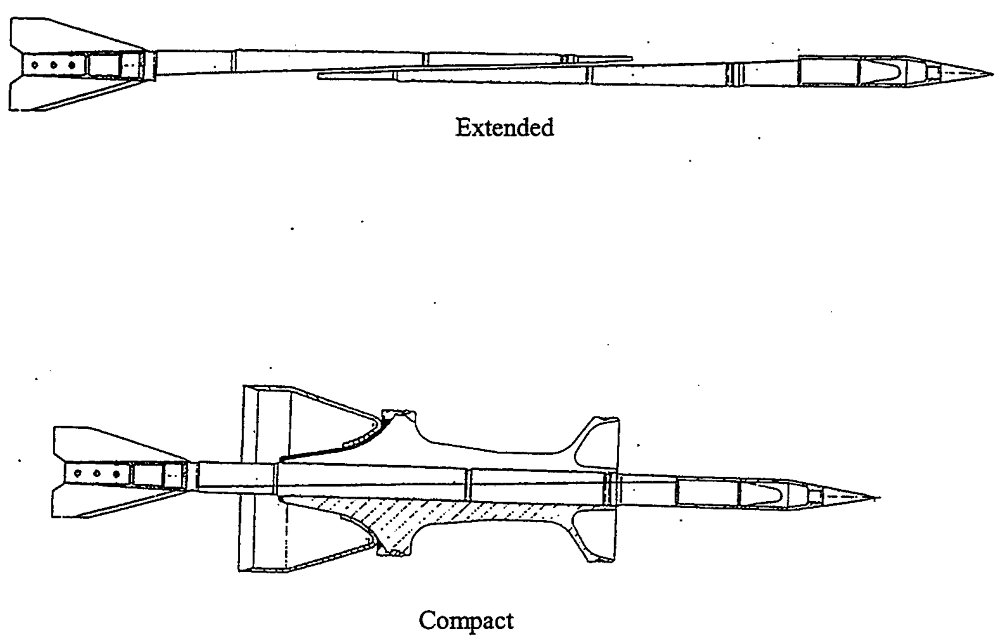


Figure 4. Split-Rod Projectile Concept From Magness and Frank (1993).

4. Cross-Section Penetrators

Penetrators with cross-sections different from a solid circle have been designed for various reasons. Tubular penetrators were examined on their own merits by Franzen and Schneidewind (1991), and a tubular penetrator is also part of an extending rod concept. Other cross-section shapes may result from different extending rod concepts, such as the split-rod concept.

The same argument that was given concerning length vs. density was examined for a novel cross-section rod by Silsby (1996). Here, the penetration performance of a solid L/D = 4 tungsten rod was compared to that of an equal-mass, equal-outer-diameter L/D = 5 tungsten rod that had holes drilled parallel to the rod axis (H-rod). In the 1.6–1.7 km/s impact velocity range, penetration experiments showed that the H-rod performance was only slightly higher than the performance of the L/D = 4 rod. A performance comparison was carried out at both 1.6 and 2.5 km/s for these two rods using the CTH code. The calculated results showed little difference in performance at 1.6 km/s, but a 10% increase in performance for the H-rod at 2.5 km/s. Using equation 11 with 17.71 g/cm^3 as the solid rod density and 14.13 g/cm^3 as the effective H-rod density gives

$$P1/P2 = \sqrt{(\rho 2/\rho 1)} = \sqrt{(17.71/14.13)} = 1.12, \qquad (12)$$

consistent with the high-velocity CTH calculation.

Bless et al. (1995) compared the penetration performance of a triform and cruciform cross-section rod with a baseline circular cross-section rod of equal mass and length. The configurations, taken from their report, are shown in Figure 5. Both numerical and experimental results indicated that there was very little difference in solid RHA penetration performance among these penetrators. The main benefit of the novel penetrators examined might be that their increased stiffness affords some resistance to the lateral forces applied to the penetrator by oblique or reactive armor targets. As with the H-rod, it is expected that an equal-mass, equal-outer-diameter cruciform or triform

Figure 5. Novel Penetrator Geometries From Bless et al. (1995).

rod would outperform a solid, circular cross-section rod of the same material in terms of RHA penetration at high velocity.

5. Segmented Penetrators

Perhaps one of the most widely researched novel penetrators is the segmented rod. One of the earliest works in this area was conducted by Kucher (1981), and a review article by Strobel (1991) on the Defense Advanced Research Projects Agency (DARPA) segmented rod program lists 33 references. In a more recent article, Bjerke et al. (1992) list 38 references concerning segmented rod performance. Not all of this work can be covered in detail here; however, the general advantages and disadvantages of this concept based on the work to date are indicated.

The fundamental advantage of segmented rod penetrators is that, theoretically, they are not limited in penetration depth at high velocity to the classic density law (equation 1). Equation 7 gives a rough idea of the high-velocity dependence of L/D = 1 penetrators, and the velocity dependence has been given a more thorough treatment for all velocities by Frank and Zook (1990). The general segmented rod concept is to have a long string of low L/D rods hit the target sequentially at the same point. Initial estimates of penetrator performance for this concept were made with analytical models and computer calculations where none of the experimental difficulties with launching the segments and maintaining their alignment were encountered. They showed significant gains in penetration efficiency (P/L) against solid steel targets. Experiments by Bjerke et al. (1992) indicated that segments of L/D lower than one gave even greater penetration efficiency than that for segments with L/D = 1.

As the potential for penetrator performance with segmented rods was examined more closely, difficulties were encountered which made the practical application of the concept problematic. It was realized that for the concept to have value, the segmented rod must be launched in a compact state and then extended during flight, preferably near the target, to reduce aerodynamic problems. While several ingenious ways to extend the segmented-rod were devised, the expense and complexity of them were drawbacks. One segmented rod configuration presented by Lynch et al. (1995) was, in effect, a series of rod-tube penetrators they called a segmented, telescopic rod. A schematic of three segments of a segmented telescopic rod concept (extended) is shown in Figure 6. This concept had the advantage that the segments could be nested together at launch and then separated with some mechanical or pyrotechnic device, given proper fuzing.

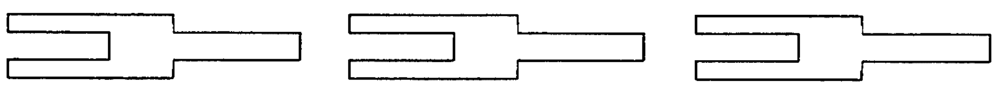


Figure 6. Three Segments of a Segmented Telescopic Rod.

Anderson et al. (1997) conducted an extensive investigation of the penetration mechanics of the segmented telescopic rod concept (seg-tel concept). They concluded from a series of hydrocode calculations and experiments that the seg-tel concept provided significant potential for improved penetration efficiency compared to an equivalent long rod; the amount of improvement was calculated to be 33% at 2.5 km/s. This amount of improvement was found for a three-piece seg-tel penetrator, even though there was a 23% degradation in penetration efficiency of the three-piece seg-tel penetrator compared to that of a single seg-tel penetrator segment.

If the segmented rod extends in flight and leaves the individual segments unconstrained, then there is difficulty in having all the segments enter the same penetration channel in the target. This problem is easily avoided in computer simulations. The compact rod is extended at a time when it has some yaw (and/or yaw rate). This implies that the individual segments are given a radial component of velocity that leads to their missing the intended impact point. The individual segments may not be aerodynamically stable, in which case they may stray even further from the impact point. Alignment problems affecting segmented rod performance should not be surprising, considering the fact that particulated-shaped charge jet performance decreases with increasing standoff.

The segmented-rod concept must be considered primarily a high-velocity concept. This is because at low velocity, individual segments do not readily flow away from the bottom of the penetration cavity and tend to interfere with subsequent segment impacts (see de Rosset and Sherrick 1996). Thus, the penetration depth for a segmented rod with n segments at ordnance velocity is less than n times the individual penetration depth of a single segment.

So far, the discussion of segmented rods has dealt only with their performance against solid steel targets. One can also imagine a segmented rod concept that is especially designed to defeat a specific threat target. For instance, consider a target made up of oblique, spaced plates. In this case, a given segment could be designed to perforate a given plate. A sufficient number of segments would be included so that the final portion of the penetrator perforated the vehicle's final protection layer. Unfortunately, this approach cannot deal effectively with the variety of possible targets that might be encountered or even different aspects of the same vehicle that have different armor designs. Another type of armor design to consider is one that attacks the penetrator from the side. In this instance, the armor design might be very effective against a segmented rod because the rod, in its extended configuration, has very little resistance to side loads.

6. Tandem Rods

Tandem-shaped charge warheads have been developed to counter the effects of advanced armor on shaped charges, and it is reasonable to expect that the same principle can be applied to kinetic-energy penetrators. Lehr and Merkel (1992) have thoroughly examined the kinematics and aerodynamics of separating rods in flight. They also discuss tandem concepts featuring a shaped charge as the leading element. Their concept has the tandem projectile separating near the gun muzzle and flying independently to the target. The drag coefficients of each element of the tandem projectile are adjusted to achieve the proper spacing at target impact. The authors note that other solutions to the problem are possible if the separation occurs further downrange.

A tandem rod might be thought of as a special case of a rod with just two segments. However, there is a distinct difference. The segmented rod concept relies on high velocity to achieve its increased performance against monolithic targets, whereas a tandem rod is specifically designed to defeat a certain class of advanced armor at a given velocity. Figure 7 shows an example of a tandem rod attacking a reactive armor target.

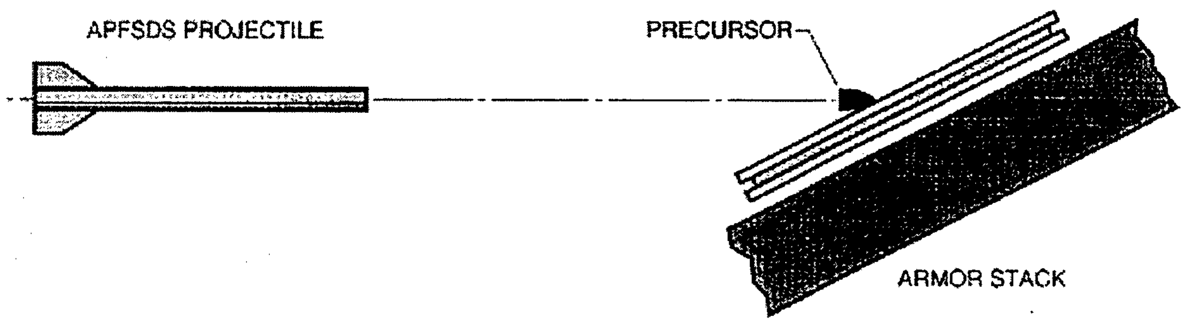


Figure 7. Tandem-Rod Concept From Menna and King (1993).

The idea behind the tandem-rod concept has little to do with the basic penetration mechanics presented in section 2. Rather, it relies on having the leading element disrupt or interfere with the defeat mechanism employed by the specific target, usually found near the front of the target. The trailing element or main body of the tandem rod must be able to go on to defeat the rear of the target in the usual way. In the case of a reactive armor appliqué, the leading element of the tandem rod detonates the appliqué, and the flying plates move out of the path of the main penetrator before it impacts the basal or backup armor. In the case of ceramic armors that are designed to defeat the penetrator by total erosion on a hard surface (Hauver et al., to be published), the leading element alters the conditions under which the total erosion is made possible, and the main body of the penetrator is able to penetrate through the hard layer. In the case of momentum-transfer armor, the leading element of the tandem rod can disrupt the timing of the devices used to launch the momentum-transfer bars.

Tandem rods are similar to segmented rods in that they are ideally launched in a compact state and then separated near the target. Thus, the same inherent deployment difficulties, such as sensing the target and activating the separation mechanism, are also present with the tandem rod. There is also the issue of robustness. That is, can the particular design of tandem rod defeat the wide variety of possible armor arrays it is liable to encounter on the battlefield? The armor designer has a certain amount of latitude to adjust his design to counter the leading element of the tandem rod if the leading element design is known. The goal of the penetrator designer is to make it too difficult or costly for armor design countermeasures to be made. Finally, both elements of the tandem rod must hit the target close enough to the same impact point to be effective. This problem may not be so large as compared to that of a long string of low L/D projectiles, but it still must be considered in the design of the tandem rod.

7. Sheathed Penetrators

The preferred embodiment of a sheathed or jacketed penetrator is to have a high-density core surrounded by a lower-density cladding material that contributes in some way to the rod's performance. The use of a sheathed penetrator with a low-density core, such as a tubular penetrator, is not discussed in this section. The sheathed penetrator is not a new concept. An example of a sheathed penetrator, the M735, is shown in Figure 8. This round of ammunition, featuring the sheathed penetrator, was fielded in the mid 1970s.

If a sheathed rod's average bulk density could be used in the penetration equations presented in section 2, then equation 11 says that the penetration performance of a high-velocity sheathed penetrator is greater than that of an equal mass, equal diameter, higher-density long rod. At lower velocities, the situation is relatively complicated. Sorensen et al. (1994) showed in a computational

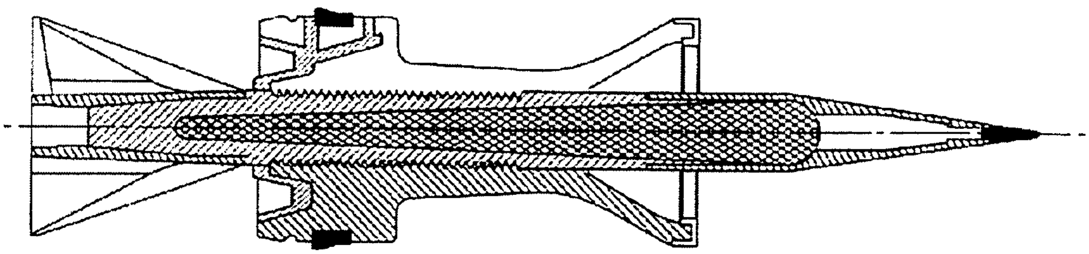


Figure 8. Schematic of the M735 Projectile.

study that at ordnance velocity, the penetration efficiency of a constant energy sheathed rod (steel sheath around a depleted uranium core) actually increases slightly with increasing sheath thickness and then decreases rapidly. The maximum value of P/L in this situation occurs at about T/D = .15, where T is the sheath thickness. For a constant-velocity sheathed rod, the penetration efficiency never exceeds that of an equivalent monolithic DU rod. The important result of the study was that there was a range of T/D ratios where the presence of a sheath did not adversely affect penetration performance. Consequently, in those situations where a sheath might have some ancillary advantage, the use of a sheath could be considered.

What advantages could be obtained by using a sheath? First, it would give added strength to a brittle core material, such as tungsten carbide, that might otherwise shatter when attacking a spaced target. The sheath could give increased resistance to bending of high L/D ratio penetrators, not only through an increase in penetrator diameter, but also through the modulus of the sheath material. This would help in the launch and flight stability of the penetrator. It has also been suggested that the sheath might help to resist lateral forces imposed on the penetrator by some types of advanced armors. Finally, Sorensen et al. (1998) have shown that from a system viewpoint, the use of a sheath can lead to an increase in muzzle velocity as compared to that obtained with a monolithic rod.

The major technical barrier to using a sheathed rod is how to manufacture it with a strong mechanical bond between the core and sheath in a cost-effective manner. A press-fit approach is relatively inexpensive, but does not provide the bond strength that is believed to be required.

Explosively-clad sheaths would provide a strong bond, but this approach is not very amenable to mass production. Machining a threaded interface might also give an acceptable bond strength but is expensive. Soldering or brazing the core and sheath is inexpensive, but does not give a high bond strength. Forming the sheath by chemical vapor deposition is a promising technique, and more research is needed to realize its full potential.

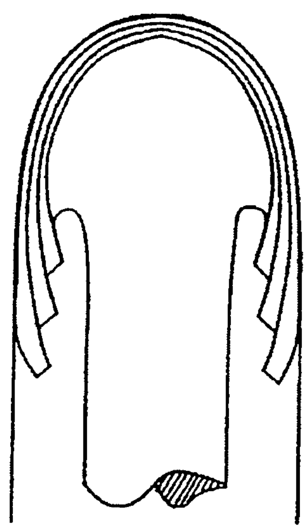
8. Penetrator Materials

Penetrator materials are not usually associated with novel penetrator concepts. However, the goal of both penetrator materials research and novel penetrator development is to increase the lethality of tank-fired kinetic energy ammunition. In addition, material properties sometimes play a key role in how a novel penetrator concept, such as a sheathed rod, is designed. Consequently, a discussion of penetrator materials falls within the scope of this report.

The primary penetrator material property for penetration performance is density, as indicated in equation 1. For this reason, materials such as tungsten and depleted uranium have been the materials of choice for kinetic-energy tank ammunition.

In some instances, a penetrator with high strength and density impacting a low-density, low-strength target results in what is called rigid-body penetration. In contrast to the eroding rod, the penetrator goes through the target undeformed. Very high penetration efficiency can occur in these instances. Besides the penetrator and target-material properties, the penetrator nose shape and velocity also are important factors in rigid body penetration. As impact velocity is increased, the mode of penetration eventually changes from rigid body to eroding rod, with an immediate decrease in penetration efficiency. The armor materials encountered with main battle tanks, along with high-impact velocities, generally preclude rigid-body penetration.

The relation between penetrator strength and penetration performance can be quite complicated and is not generally described with one-dimensional penetration models. For instance, Magness and Farrand (1990) found that large changes in the mechanical properties of tungsten alloys did not significantly affect their performance against RHA. However, increasing the hardness of depleted uranium did increase its performance. The explanation for the difference in behavior was ascribed to the fundamental difference in which these two materials deform at high strain rates. These differences are shown schematically in Figure 9. Simply stated, depleted uranium forms a "self-sharpening" nose that requires less energy to penetrate the target, whereas tungsten forms a "mushroom" nose that requires more energy to penetrate the target. The effect is accentuated for depleted uranium as its hardness increases.



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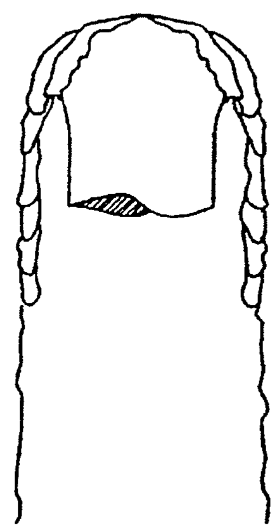

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Figure 9. Deformation Behavior of Tungsten (A) and Uranium (B) From Magness and Farrand (1990).

Depleted uranium is viewed as environmentally hazardous due to the low levels of radiation that it emits. Consequently, the challenge has been to replace it with a material that has high density and the same mechanical properties as depleted uranium but is environmentally benign. No such material has been developed to date, but the performance gap between depleted uranium and other high-density alloys has been narrowed.

9. Summary

Many novel concepts appear to work best against monolithic targets at high velocity. These concepts include the rod-tube, segmented penetrator, sheathed penetrator, and H-rod. Their increased performance at high velocity is documented and well understood. But fully implementing these particular concepts at any velocity has posed a major engineering or fabrication challenge.

The basic principles of penetration mechanics can be expressed in terms of one-dimensional semiempirical penetration models. These models involve targets that are monolithic materials at normal obliquity. Many modern tank armors contain multimaterial, spaced armor at obliquity. The principles may not be of great use when applied to this portion of the armor design, but are useful in analyzing the interaction of the residual penetrator with the monolithic, rolled, homogeneous armor portion of the target.

Certain novel penetrator concepts, such as the tandem rod, can be designed to counter the effects of specific advanced armor technologies. The challenge to the penetrator designer here is to make sure that there is no easily employed countermeasure and that the novel concept will be effective against a range of other possible armor threats.

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REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 2001	Final, October 1999 - December 1999

4. TITLE AND SUBTITLE
An Overview of Novel Penetrator Technology

5. FUNDING NUMBERS
1L162618AH80

6. AUTHOR(S)

William S. de Rosset

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WM-MD
Aberdeen Proving Ground, 21001-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2395

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Over the past 25 years, long-rod penetrators have proven to be highly effective when used as lethal mechanisms in tank-fired ammunition. However, constraints imposed by currently fielded gun systems and the possibility of future, high-velocity gun systems have prompted researchers to examine other penetrator concepts. The rationale for some of these concepts can be found in physical principles embodied in simple one-dimensional semiempirical penetration models. In other cases, certain vulnerabilities of advanced armors can be attacked with novel concepts. In any event, it has been found that departure from a simple, long rod has posed engineering and fabrication problems that make implementation of the concepts at full scale a major technical challenge.

14. SUBJECT TERMS
hypervelocity impact, penetrator concept, kinetic energy penetrator, penetration mechanics

15. NUMBER OF PAGES
34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

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