Chapter Three

Introduction to Kinetic Energy Projectile
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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.

Fig.1 shows the sabot, obturator (seal), nose tip, and fins. The sabot carries the sub-projectile down the gun tube and is discarded shortly after muzzle exit. The fins give flight stability, and the nose reduces aerodynamic drag. 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.

**Fig.1- Schematic of the M829Al Projectile**

A penetrator may also be considered novel if it is made of a material which
has unusual penetrating characteristics.

3.1 State of the Art and Modern Design

The APDS was initially the main design of KE penetrator [APDS stands for Armor Piercing Discarding Sabot]. APDS was originally designed as an anti-tank or anti-armor munition. Adding fins like the fletching of an arrow to the base gives the round stability hence Armour-Piercing Fin-Stabilized Discarding Sabot (APFSDS). The spin from rifling decreases the effective penetration of these rounds (rifling diverts some of the linear kinetic energy to rotational kinetic energy, thus decreasing the round's velocity and impact energy) and so they are generally fired from smoothbore guns. Another reason for the use of smoothbore guns is that shaped charge HEAT munitions lose much of their effect to rotation. APFSDs can still be fired from rifled guns but the sabot is of a modified design incorporating bearings to isolate the spin of the sabot in the barrel from the round itself, so far as practicable. Rifled guns have been kept in use by some nations (the UK and India, for example) because they are able to fire other ammunition such as HESH rounds with greater accuracy. However, the rifling wears down under regular APFSDs use and requires more maintenance. For these reasons the British Challenger 2 is being trialled with a Rheinmetall 120mm smoothbore gun.

KE penetrators for modern tanks are commonly 2–3 cm in diameter, and 50–60 cm long; as more modern penetrators are developed, their length tends to increase and the diameter to decrease. However the development of heavy forms of reactive armour such as the Soviet/Russian Kontakt-5 which were designed to shear long rod penetrators has prompted the reversal of this trend in the newest U.S. rounds. To maximize the amount of kinetic energy
released on the target, the penetrator must be made of a dense material, such as tungsten carbide or depleted uranium (DU) alloy (Staballoy)

3. 2 A Modeling of penetration of KE. Projectile

3.2.1 Flow stress and the Poncelet form

One may calculate the interface force, $F$, upon a projectile as the target’s averaged flow stress applied over the directional component of the projectile’s wetted area, to obtain

$$ F/A_{pw} = \kappa_t \rho_t u^2 + R_t $$

where $A_{pw}$ is the wetted area of the projectile, projected onto a plane perpendicular to the velocity vector, $\kappa_t$ is the target-flow “shape factor,” $\rho_t$ is the target density, $u$ is the penetration velocity, and $R_t$ is the so-called target resistance, an integrated amalgam of the deviatoric stress field developed in the target. For ductile eroding targets, many analyses have suggested (and experiments have supported) that the target resistance can be treated as a constant (i.e., independent of penetration velocity) whose magnitude is in the range of four to six times the uniaxial flow stress of the material. When the projectile erodes, the eroding nose of the projectile assumes a roughly hemispherical shape which is fully wetted by the erosion products. In this circumstance, one may reasonably assume that $A_{pw}$ approaches the cross-sectional area of the projectile, $A_p$, and that $\kappa_t$ approaches the value of 0.5 associated with the Bernoulli stagnation pressure. The result is that the decelerative stress averaged over the cross section is given by

$$ \bar{\sigma} = F/A_p = 1/2 \rho_t u^2 + R_t $$

Such a result is seen, for example, as part of the stress balance in the so-called
extended-Bernoulli equation used by Tate [88] and others. If, however, the projectile remains rigid during the penetration event, then a different set of simplifications apply. While it is deduced that the penetration velocity, $u$, must equal the projectile velocity, $V$, no simplifications are obvious regarding the shape factor and wetted area, $\kappa_t$ and $A_{pw}$, respectively. Thus, the cross-section-averaged decelerative stress is

$$\bar{\sigma} = \frac{F}{A_p} = (\kappa_t \rho_t v^2 + R_t) \cdot \frac{A_{pw}}{A_p} \quad (3-3)$$

When this equation is approximated by taking $A_{pw}$ as $A_p$, with constant values of $\kappa_t$ and $R_t$, and when it is used as the decelerative stress acting upon the cross section of a rigid projectile, the form the equation takes is known as the Poncelet form. The Poncelet form looks like

$$-M \dot{v} = B v^2 + C \quad (3-4)$$

and is traditionally solved by expressing the acceleration $\dot{v}$ as $v(dv/dx)$, where $x$ is the coordinate of penetration. Given a striking velocity, $v_0$, the solution yields the penetration depth as a function of the current velocity:

$$x(v) = \frac{M}{2B} \ln \left( \frac{c+Bv_0^2}{c+Bv^2} \right) \quad (3-5)$$

The final penetration depth is obtained when the instantaneous velocity, $V$ drops to zero, to yield

$$p(v_0) = \frac{M}{2B} \ln \left( 1 + \frac{B}{c} v_0^2 \right) \quad (3-6)$$

Segletes and Walters [89] also offered a time-dependent explicit solution to the Poncelet form (i.e., in terms of $v(t)$ and $x(t)$, where $t$ is the time variable) when they solved for the residual rigid-body penetration phase of an otherwise eroding-body event. The form of their solution, using the nomenclature of equation (3-4), is

$$v(t) = \sqrt{\frac{c}{B}} \tan \left[ \sqrt{\frac{BC}{M}} (t_f - t) \right] \quad (3-7)$$
and \[ x(t) = \frac{M}{B} \left\{ \ln \cos \left( \frac{\sqrt{BC}}{M} (t_f - t) \right) - \ln \cos \left( \frac{\sqrt{BC}}{M} t_f \right) \right\} \] (3-8)

where the event duration, \( t_f \), is given by

\[ t_f = \frac{M}{\sqrt{BC}} \tan^{-1} \left( v_0 \sqrt{\frac{B}{C}} \right) \] (3-9)

It can be shown, through trigonometric substitution that \( x \) for the case of \( v = 0 \) in equation (3-5) is identical to \( x \) for the case of \( t = t_f \) in equation (3-8). This is as it should be since the total penetration should not depend on whether \( v \) was integrated over \( t \) or \( x \).

### 3.3 Examples of 25 mm Ammunition with details

<table>
<thead>
<tr>
<th>Cartridge weight (nominal)</th>
<th>Muzzle velocity (nominal)</th>
<th>Chamber pressure (typical)</th>
<th>Trace (typical)</th>
<th>Dispersion (typical)</th>
<th>Penetration (typical)</th>
<th>Fuze type</th>
<th>Time of flight (2000m)</th>
<th>NSN</th>
</tr>
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<tbody>
<tr>
<td>M791 APDS-T Armor-Piercing Discarding Sabot with Trace</td>
<td>455g</td>
<td>1345 m/s</td>
<td>410 MPa</td>
<td>2.2 sec</td>
<td>.30 x .30 mr</td>
<td>25mm RHA @ 60° 1300m</td>
<td>1.7 sec</td>
<td>1035-01-380-8960</td>
</tr>
<tr>
<td>M792 HEI-T High-Explosive Incendiary with Tracer</td>
<td>493g</td>
<td>1100 m/s</td>
<td>360 MPa</td>
<td>6.0 sec</td>
<td>.55 x .55 mr</td>
<td>NA</td>
<td>3.6 sec</td>
<td>1305-01-380-9884</td>
</tr>
<tr>
<td>M793 TP-T Target Practice Discarding Sabot with Tracer</td>
<td>492g</td>
<td>1100 m/s</td>
<td>360 MPa</td>
<td>6.0 sec</td>
<td>.30 x .30 mr</td>
<td>NA</td>
<td>3.6 sec</td>
<td>1330-01-380-5862</td>
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<tr>
<td>M910 TPDS-T Target Practice Discarding Sabot with Tracer</td>
<td>415g</td>
<td>1100 m/s</td>
<td>360 MPa</td>
<td>4.0 sec</td>
<td>.30 x .30 mr</td>
<td>NA</td>
<td>3.6 sec</td>
<td>1305-01-426-4359</td>
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<tr>
<td>PGU-32/U SAPHEI-T Semi-Armor piercing High Explosive Incendiary–Traced</td>
<td>493g</td>
<td>1100 m/s</td>
<td>360 MPa</td>
<td>5.5 sec</td>
<td>.45 x .45 mr</td>
<td>13mm RHA @ 30° 1000m</td>
<td>1.9 sec</td>
<td>1305-01-356-9083</td>
</tr>
</tbody>
</table>

### The 25mm Ammunition Family

- M791 APDS-T
- M792 HEI-T
- M793 TP-T
- M910 TPDS-T
- PGU-32/U SAPHEI-T
3.4 Penetration Mechanics Principles

One-dimensional modeling of the penetration process was carried out independently by both Alekseevskii [90] and Tate [88], who are credited with including the effects of target resistance and penetrator strength in formulating penetration equations. Wright and Frank [91] helped to quantitatively describe the makeup of the target resistance. Using the formulation of Christman and Gehring [92], Frank and Zook [93] were able to reproduce the experimentally observed effect of length-to-diameter ratio (L/D). Later work by Walker and Anderson [94] included transient effects in their formulation. More recently, Segletes and Walters [95] solved the momentum equation in a noninertial reference frame, thus simplifying the mathematical solution obtained earlier by Walker and Anderson [94]. 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, semi-empirical 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:

$$ P = L\sqrt{\frac{\rho_p}{\rho_t}} $$

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.

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 [96],

\[ F(v) = \exp\left(-\frac{b}{v^2}\right) \]  

hereafter referred to as the Odermatt function. Lanz and Odermati[96] developed an original equation to predict the limit thickness of armor plate being perforated by large-caliber penetrators. 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 \( v \to \infty \), 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

\[ P = L\sqrt{\xi}\exp\left(-\frac{b}{v^2}\right) \]  

More recently, penetration data have been fitted by Rapacki et al. [97] to the Odermatt function using

\[ b = 2S/\rho \]  

Where \( \rho \) is the penetrator density, and \( S \) is related to the target strength through the equation

\[ S = q \cdot (BHN)^m \]  

Here, \( q \) and \( m \) are fitting parameters, and BHN is the Brinnell hardness of the target. At high velocity, Frank [98] has made certain approximations to show that

\[ b \approx \left(1 + \sqrt{\xi}\right)\frac{(H - Y)}{k\rho} \]  

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 (3-12) 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 (3-12), 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

\[
P/D = c.\rho^{1/3}.v^{2/3}
\]  

(3-16)

where \( c \) is a constant involving the rod geometry and the proportionality constant. Equation (3-16) indicates that penetration depth increases as \( v^{2/3} \), whereas equation (3-12) 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 (3-12), and then identifying the final transient penetration phase (involving approximately one penetrator diameter) to equation (3-16). A heuristic penetration formula, similar in form to that given by Frank and Zook [99] that explicitly contains the effects of \( L/D \) ratio is then

\[
P = L.\left(1 - \frac{D}{L}\right).\sqrt{\xi} \exp\left(-\frac{b}{v^2}\right) + D.c.\rho^{1/3}.v^{2/3}
\]  

(3-17)

3.5 Classification of projectile

Projectiles can be characterized according to the method of launching and the commodity that is delivered. The means for setting them in motion are projection from guns (bullets, shells, grenades), drops from a parent vehicle (bombs, mines), and self-projecting devices (missiles, rockets, torpedoes). The
commodity to be delivered by a projectile solely designed to penetrate is its kinetic energy. It is an explosive or incendiary warhead for projectiles that are intended to approach but not penetrate a target. It is a combination of both kinetic energy and warhead for penetrating weapons that count on explosive or incendiary effects to contribute to the dysfunction of the target.

3.5.1 Kinetic energy penetrators

Examples of projectiles that are designed for efficiency of penetration of targets are shown in Fig.2. Armor-piercing projectiles have a hard core to which other components are attached that serve exterior and interior ballistic purposes, for example a rotating band for spin stabilization, a windscreen for aerodynamic efficiency, and a tracer unit to make the trajectory visible.
Figure 3 shows typical deformation of projectiles after impacts against SAE 4130 steel plates (230 BHN) of up to 6.35mm thickness and at obliquities up to 60°. Compressive deformations and shattering occurs near normal obliquity, while bending and associated fracturing occurs at significant obliquity.

More literature on KE projectile can be found in Refs.[100-119].