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Method for Kinetic Armour-Piercing Munitions Effectiveness Estimation

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***Abstract.* This paper presents a mathematical model and a computational module for armour-piercing munition (APM) effectiveness estimation. The topicality of this research arises from the necessity to automate the weaponeering process as part of Phase 3 of the Joint Targeting Cycle. The main objective of the study is to analyse the penetrator's structural material and munition's geometric characteristics impact over the depth of penetration into homogeneous steel armour plate Class I, in accordance with MIL-DTL-46100E/2008 standard. Scientific methods analysis, math modelling, data collection, simulation and synthesis were used during the study. As a result, the following cconclusions were made: 1) the armour-piercing munitions' effectiveness depends mainly on the ratio between penetrating rod's density and the armour density, but not on the hardness of their penetrating elements; 2) the proposed model is an approximate empirical technique for armor-piercing munition effectiveness estimation; 3) iteratively finding solutions for different input variables makes it possible to determine the input conditions necessary to realize the desired damage effect on a target; 4) the computational module could be applied to the weaponeering process as part of the Joint Targeting Cycle.**

Keywords: weaponeering, engagement, penetration.

I. INTRODUCTION

Joint targeting is a process to select and prioritize targets and determine proper means to engage them in accordance with the existing operational requirements and available capabilities [1]-[3]. It is a logical sequence of steps that supports decision making by linking operation objectives and effects to achieve them, with appropriate kinetic or non-kinetic means of engagement over prioritized targets. Therefore, a key part of the process is the weaponeering.

Weaponeering defines the type and quantity of weapons required to achieve desired effect on a given target, taking into account its vulnerability, munition's damage effect, reliability, environmental conditions and engagement accuracy [4].

To estimate a weapon capability to realize a desired hypothesis (degree) of damage, it is necessary to know its effectiveness and target vulnerability. These are based on the results of statistical analysis and simulations, outcome of which are values for munition's general and partial damage effect characteristics [5].

II. MATERIALS AND METHODS

A. Area of Research

Depending on their damage effect, kinetic weapons are classified into two groups [7]:

- contact munitions – inflict target damage in case of a direct hit (cumulative, armour-piercing, concrete-penetrating, etc.);

- remote munitions – damage the targets when their warheads detonate at a certain distance from it (fragmentation, blast, incendiary, etc.).

The study comprises analysis of the damage mechanism of penetrating armour-piercing munitions. It resulted in creation of a computational module for determining their penetrating effect, that can be used for weaponeering needs.

B. Armour-piercing Munitions

Important feature of APMs (calibre and sub-calibre) is the ability to penetrate the target at the expense of their kinetic energy. They are widely used against heavy and light-armoured targets by penetrating their armour protection and subsequently defeating vulnerable components and crew located within. Ideally, an APM equipped with explosive should penetrate the armour and detonate afterwards, causing damage from the resulting fragments, shock wave, and incendiary effect. When a non-explosive APM is used, the defeat of the target is achieved by mechanical impact of the weapon's core and debris formed because of the armour destruction [7].

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In that case, damaging element is a high hardness armour-piercing core made of ultra-high strength steel (UHSS), tungsten, Ni or Co added tungsten carbide, or depleted uranium. A key factor determining its effectiveness is the kinetic energy on impact, so the core should have low drag, relatively large mass compared to other munitions, and a high muzzle velocity in the range of 700-1785 m/s or more. Important trend in APM development over the years is the increase of the working length and diameter ratio of the penetrator. The initial values of about 13:1 for the Russian/Soviet 3BM3 and 3BM6 gradually increased to 40:1 for the modern US M829A2 with a depleted uranium penetrator, where the impact energy reaches 35,800 [7]. Fig. 1 shows geometrical characteristics of an APM.

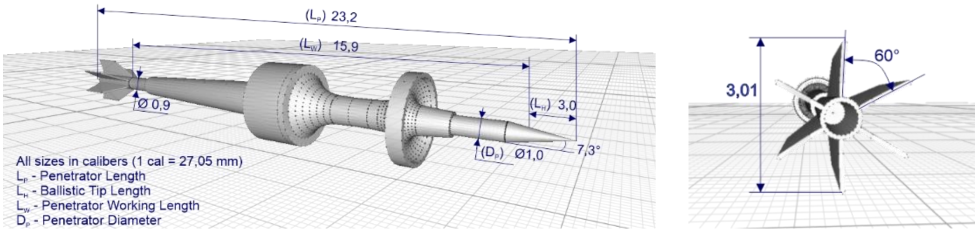

Fig. 1. APM geometric characteristics.

C. Math Model

To study the APM penetration parameters the following assumptions have been made:

- the munition structure does not deform on impact;

- no loss of kinetic energy to deform the armour and destroy its fasteners;

- the conversion of kinetic energy to thermal energy is negligible;

- the munition longitudinal axis nutation, Coriolis force, Magnus effect and wind effect are ignored.

As moving along its trajectory, the APM speed constantly decreases due to the aerodynamic drag, which depends on the munition's middle cross section, angle of attack (in theory 0°) and drag coefficient. If suppose that its horizontal and vertical movement are independent, the initial velocity along both axes is determined as follows [4]:

$$v_{0x} = v_a \cos\gamma - v_e \sin\gamma \qquad (1)$$

$$v_{0y} = v_a \sin\gamma + v_e \cos\gamma \qquad (2)$$

where: v_{0x}-initial horizontal velocity [m/s]; v_{0y}-initial vertical velocity [m/s]; v_a-carrier velocity [m/s]; v_e-release velocity [m/s]; γ-trajectory inclination relative to the ground surface [deg].

In that way, the horizontal, vertical and total velocities on APM impact at a target, i.e., at a point with linear coordinates x and y would be:

$$\begin{gathered} V_i(x) = v_{0x}.e^{\left(-\frac{c_d.S_m.\rho}{2G\sin\gamma}x\right)} \\ V_i(y) = v_{0y}.e^{\left(-\frac{c_d.S_m.\rho}{2G\cos\gamma}y\right)} \\ V_i(\Sigma) = \sqrt{V_i(x)^2 + V_i(y)^2} \end{gathered} \qquad (3)$$

where: c_d-drag coefficient; S_m-area of the munition middle cross section [m^2]; ρ-air density [kg/m^3]; G-munition weight [kg].

To calculate the speed of impact required for penetration through homogeneous armour the Lambert's equation is used [8]:

$$v_p = 4000\left(\frac{L_p}{d_a}\right)^{0,15}\sqrt{\left(\frac{D_p^3}{m_p}\right)}\left[\left(\frac{d_a}{D_p}\right)\left(\frac{1}{\cos\theta}\right)^{0,75} + \mathrm{e}^{\left(-\frac{d_a}{D_p}\left(\frac{1}{\cos\theta}\right)^{0,75}\right)} - 1\right] \qquad (4)$$

where: L_p-length [cm], D_p-diameter [cm] and m_p-mass of the penetrating rod, [g] ($m_p = \frac{\pi}{4}D_p^2 L_p \rho_p$); d_a-armour thickness along the surface normal [cm]; θ-impact angle relative to the surface normal [deg.]; ρ_p- average density of the penetrating rod [g/cm^3].

Average density values of structural materials used for penetrating rods elaboration are given in Table 1 [9].

TABLE 1 STRUCTURAL MATERIALS AVERAGE DENSITY

ρp, [g/cm³]	**Aluminum**	**UHSS**	**Depleted Uranium**	**Tungsten**
	2,7 - 3	7,9 – 7,95	19,05	19,35

In order to estimate the penetration depth of APMs with UHSS, tungsten alloy or depleted uranium rod into an armoured plate, the Lantz-Odermatt equation could be used [7]:

$$L_{dp} = L_w.k.\frac{1}{\tanh(a_0.a_1.\eta)}.(\cos\theta)^{a_2}.\sqrt{\frac{\rho_p}{\rho_a}}.e^{\left(-\frac{s^2}{v_p^2}\right)} \qquad (5)$$

where: L_w-working length of the penetrator [mm]; k-coefficient dependent and a_0, a_1, a_2-coefficients independent of the rod material; $\eta = L_w/D_p$ -length to diameter ratio of the rod; $tanh$ -hyperbolic tangent function; ρ_p-rod material density [kg/m^3]; ρ_a-armour material density [kg/m^3].

In turn, L_w is determined mathematically for two ballistic tip shapes – cylindrical and conical:

$$L_w = L_p - \Delta L \qquad (6)$$

$$\Delta L = L_h\left[1-\frac{1}{3}\left(1+\frac{d_a}{D_p}+\left(\frac{d_a}{D_p}\right)^2\right)\right] \qquad (7)$$

where: L_h-length of the ballistic tip; ΔL-relative length of the ballistic tip.

Depending on the penetrating rod material - tungsten alloy, depleted uranium ($s_{dp/v}$), or UHSS (s_{hs}), the value of s^2 is calculated with the empirical relations shown:

$$s^2_{dp/v} = \frac{(b_0 + b_1.HB_a)HB_p}{\rho_p} \qquad (8)$$

$$s^2_{hs} = \frac{b_0.HB_a^{\alpha}.HB_p^{\beta}}{\rho_p} \qquad (9)$$

where: b_0, b_1-coefficients independent of the rod material; HB_p-Brinell hardness number of the rod material; HB_a-Brinell hardness number of the armour structural material.

Values of the coefficients dependent and independent of the material properties used in equations (5), (8) and (9), are given in Table 2 [8].

TABLE 2 VALUES OF THE USED COEFFICIENTS

Coefficient	**Material of the armour-piercing rod**		
	UHSS	***Depleted Uranium***	***Tungsten***
k	1,104	0,825	0,994
b_0	9876	90,0	134,5
b_1	–	-0,0849	-0,148
α	0,3598	–	–
β	-0,2342	–	–
a_0	0,283	0,283	0,283
a_1	0,0656	0,0656	0,0656
a_2	-0,224	-0,224	-0,224

After transformation, the Lanz-Odermatt equation acquires a simpler and more convenient for analytical modeling form:

$$L_{dp} = L_w.f(\eta).(\cos\theta)^{a_2}.\sqrt{\frac{\rho_p}{\rho_a}}.e^{\left(-\frac{c.\sigma_b}{\rho_p.v_p^2}\right)} \qquad (10)$$

where the function f(η) is determined empirically by the expression [7]:

$$f(\eta) = 1 + z_1\frac{1}{\eta}\left(1-\tanh\left(\frac{\eta-10}{z_2}\right)\right) \qquad (11)$$

$$\eta = \frac{L_w}{D_p}, \qquad (12)$$

the value of the variable c – by solving the polynomial:

$$c = 22{,}1 + 1{,}274.10^{-2}.\sigma_b - 9{,}47.10^{-6}.\sigma_b^2 \qquad (13)$$

and the parameter σ_b is the tensile strength, i.e., tensile failure strength of the armor material, measured in [MPa]. For rolled homogeneous armor (RHA), the value of σ_b is about 800-1600 MPa.

An indirect approach to calculate the σ_b value for random structural material of the armor is to determine its Brinell hardness number HB_a and subsequently to use the dependences between the two parameters, valid when $HB_a \leq 500$ [8], [10]:

$$\sigma_b = 3{,}4848(HB_a - 11{,}24) \qquad (14)$$

$$HB_a = 0{,}287(\sigma_b - 39{,}1692) \qquad (15)$$

Thus, in the range of σb = 800 ÷ 1600 MPa, HBa varies from 240 to 470.

The presented dependencies make it possible to evaluate the effectiveness of an APM against targets with different types of armour protection.

D. Computational Module

The proposed mathematical model is implemented by developing a computational module in Visual Basic® environment with the following characteristics:

Purpose of the module: Armor-piercing munition effectiveness calculation.

Solved tasks: 1) Predict the penetration depth in homogeneous armor in case of armor-piercing munition impact; 2) Estimate the relation between penetration depth and the penetrating element material or L_w/D_p ratio.

III. RESULTS AND DISCUSSION

APM's effectiveness estimation in this study is based on two test scenarios.

The first scenario includes penetration depth calculation using APMs with constant geometric characteristics and different structural material of the penetrating element: 1) Steel AISI 4340; 2) Tungsten Alloy WNF-7129; 3) Depleted Uranium Alloy (U-Ti-Mo) Staballoy, in a Class I homogeneous armor plate, in accordance with MIL-DTL-46100E/2008 standard (UHTA Class I), at an impact angle $\theta = 0°$, launched from different distances as in Table 3.

TABLE 3 MECHANICAL CHARACTERISTICS

Characteristic	**AISI 4340**	**WNF-7129**	**Staballoy**	**UHTA Class I**
HB_p/HB_a	341	271	185	330
$\rho_p/\rho_a\ [kg/m^3]$	7850	16850	19070	7980
$L_p, [mm]$	350	350	350	-
$L_h, [mm]$	45	45	45	-
$D_p, [mm]$	30	30	30	-
$v_0, [m/s]$	1500	1500	1500	-

The results from the first test scenario are shown in Fig. 2.

The second experiment is aimed to the penetration depth calculation of a WNF-7129 alloy piercing munition, for different length to diameter ratio of the rod ($\eta = L_w/D_p = 10 \div 40$), with constant initial velocity $v_0 = 1800\,m/s$ and angle of impact ($\theta = 0°$) in the same homogeneous armor plate (Class I, MIL-DTL-46100E/2008) (Fig. 3).

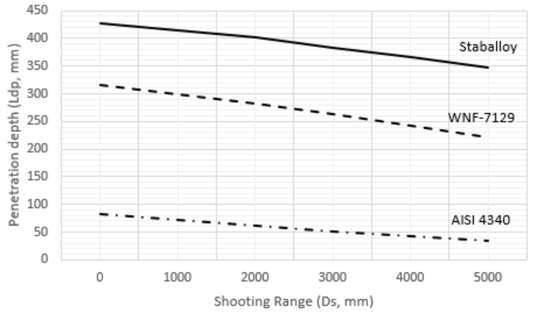

Fig. 2. Penetration depth for different structural materials of the piercing rod.

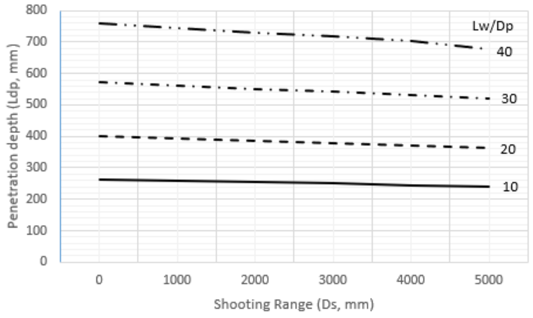

Fig. 3. Dependency between the penetration depth and the $\eta = L_w/D_p$ ratio.

IV. CONCLUSIONS

The experimental results show that a key factor affecting the effectiveness of armor-piercing munitions is not the hardness of their penetrating elements, but the ratio between penetrating rod's density and the armor density, when other conditions being equal. This determines the advantages of the contemporary munition made of tungsten alloy or depleted uranium (if don't take into consideration the harmful influence of the latter on the environment and living organisms) compared to their steel counterparts.

In addition, the test scenarios highlight also another trend in this class of ammunition development – the continuous increase of   ratio. What is more, an increase in   by 10 units leads to an increase in the penetration depth by 25%÷35%.

The proposed mathematical model and calculation module provide an approximate empirical approach to estimate the expected damage effect of an armor-piercing munition consisted of a kinetic penetrating element. Repeatedly finding solution to this direct problem with controlling the variables in the input data makes it possible to find a solution to the inverse problem as well, i.e., to determine the input conditions necessary to realize the desired damage effect on a target. Similar computational automation could be applied to the weaponeering process in Phase 3 of the Joint Targeting Cycle.

V. ACKNOWLEDGMENTS

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