doi: 10.5937/str2500003B

A Computational Study on the Influence of Explosive Type on Shaped Charge Jet Velocity in 64 mm Warhead

Muhamed Bisić [1)]
Predrag Elek [1)]

Constant development of protective materials and armored systems requires continuous improvements in the field of anti-tank ammunition development. One of the most commonly used anti-tank explosive ordnance are shaped charge projectiles/warheads. Serbia has been globally recognized for decades in the production of high-quality hand-held rocket launchers equipped with various calibers of shaped charge ammunition. One of the most famous representatives is the 64 mm hand-held rocket launcher, better known as "Zolja". Although it has been in use for decades and it has insufficient capabilities against more modern protection systems, retaining the traditional design and long-established production technologies, along with the use of more potent and modern explosives, could significantly enhance its penetration power. This paper uses analytical calculation and numerical simulation to analyze how different explosive materials affect the velocity of shaped charge jet of 64 mm M80 warhead, which ultimately directly impacts its penetration capabilities.

Key words: **shaped charge warhead, jet velocity, penetration, numerical simulation, explosive.**

Introduction

Serbia, as a large manufacturer of high-quality rocket systems, especially shaped charge warheads, constantly improves its products by performing outstanding extensive research and a lot of experiments. Shaped charges are used to pierce hard targets in all types of warfare (land, air and naval). For example, they can efficiently damage tanks possesing thick armour protection by using high explosives compositions charges to produce a thin high velocity metal jet which is used for target damage [1].

Cumulative warhead of rocket projectile M80 Zolja consists of several vital parts: piezogenerator, balistic cap, contact cap, conical shaped charge liner, housing, piezo-electric trigger, explosive charge and detonation wave shaper, Figure 1.

When the rocket strikes a target, the impact activates the initiator and detonates the warhead's explosive charge. The detonation wave propagates through the explosive, compressing the liner and forming a high-velocity primary cumulative jet, followed by a slower, more massive secondary jet. The gases produced during the explosion move behind the primary jet and, on their path, surpass the secondary jet, still having enough energy to damage the functional components of the tank, destroy the crew, and trigger an explosion of the ammunition [2].

Understanding how different explosives influence jet formation is essential for optimizing warhead performance and improving the effectiveness of shaped charge systems.

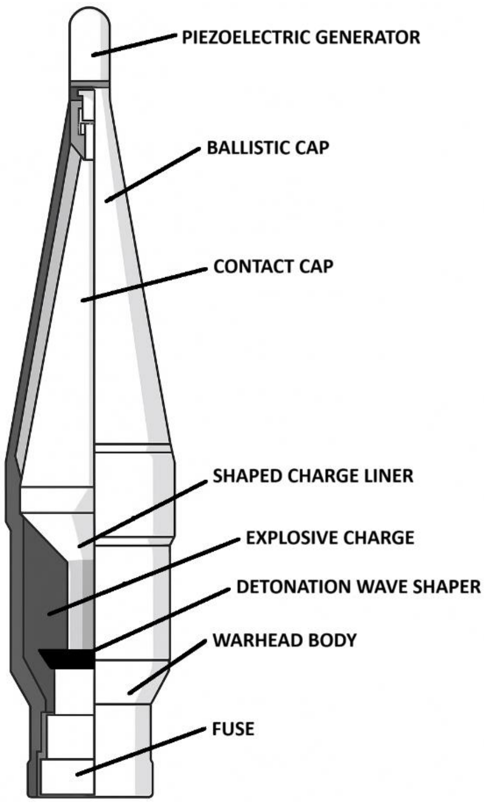

Figure 1. Elements of "Zolja" warhead [2]

[1)] Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, Belgrade, Serbia
Correspondence to: Muhamed Bisić, e-mail: mbisic@gmail.com

Explosive material

Most explosive charges in warheads contain conventional explosives: trinitrotoluene (TNT), hexogen (RDX), and octogen (HMX) as the main energetic components, along with certain additives that modify their energetic effects, stability, sensitivity and manufacturability. Hexogen and octogen fall into the category of strong secondary explosives. They are used in mixtures with TNT or are phlegmatized, in order to reduce the sensitivity of explosives to mechanical influences, making them easier to handle [3].

The cumulative projectile 64mm M80 Zolja uses phlegmatized octogen, designated FO-3S, as its main explosive charge. This composition falls into the group of plastic-bonded explosives (PBX) and consists of 95% octogen and 5% phlegmatizing agent. Due to similar performance and better data availability in simulation software, this paper uses LX-14—a PBX containing 95.5% octogen and 4.5% binder. In such formulations, phlegmatization is typically achieved using Estane 5702-F1 polyurethane elastomer or montan wax [4].

LX-14 is a secondary high explosive developed by Lawrence Livermore National Laboratory. This composition is a white solid with purple dots. The maximum theoretical density of this explosive is 1.849 g/cm^3, while the nominal density is 1.83 g/cm^3. Melting point is greater than 270°C, with decomposition. The heat of formation is 6276 J/mol. Detailed description of parameters is represented in Table 4 [5].

Explosive charger is formed using pressing technology. The explosive is directly pressed into the projectile body, which means that the explosive charge is formed by the action of pressure in one cycle. A vacuum is applied to remove the air trapped in the charge during the pressing. During direct pressing, the pressure gradient in the explosive material causes friction between the material and the inner wall of the projectile, which negatively affects the performance and sensitivity of the explosive composition [6]. The greater the ratio of height to diameter of the pressing, the problem of inhomogeneity arises. The greatest density is achieved directly under the tool plunger, while the lowest density occurs in areas lacking a die. The inhomogeneity of the pressing can be reduced by using a fork (a specific multi-pronged pressing tool) and repeating the pressing process two or three times [7].

Determination of Jet Parameters

For the purpose of this research, both analytical and numerical calculations are used in order to get more precise results and compare different approaches.

Analytical calculation

The BASC (BRL Analytical Shaped Charge) program [8] was developed in 1981 and contains several analytical models for assessing the parameters of shaped charge jets and their penetrative capability. The formation of the jet is estimated based on the PER (Pugh, Eichelberger, Rostoker, 1952) theory, while the Alekseevskii-Tate model gives the final velocity of the jet as well as the entire acceleration process of the jet [9, 10]. For assessing penetration capability, the DSM (DiPersio, Simon, Merendino) model is used, while the Alekseevskii-Tate model is used to evaluate the shape of the cavity in the target [10, 11]. The program first determines the angle of collapse of the liner that occurs due to the movement of the detonation wave at a speed D. To successfully determine the angle of collapse of the liner, certain geometric parameters and characteristics of the explosive used are required. Here, one of the shortcomings of the BASC and its modificated version used in this research arises. These programs consider only a constant thickness of the liner, which is generally not the case in real projectiles, so it is necessary to determine an equivalent liner that will have the same mass as the real one but with constant thickness before running the program. Moreover, it is necessary to use some empirically determined constants in the program since it is extremely difficult to obtain experimental data. The jet breakup time is calculated based on empirically established expressions as experimental research using X-rays is hard to access [8].

The PER theory represents a modified Birkhoff model, which represents a variable, rather than constant, rate of liner collapse during the detonation of the cumulative charge [12]. This model assumes that the rate of liner collapse decreases continuously from the tip of the liner to its base, resulting in an elongation of the jet. The PER theory has been experimentally validated and today it represents the basic analytical model for forming shaped charge jets [7].

The hydrodynamic model of the Alekseevskii-Tate is similar to the Birkhoff's theory. It is assumed that the length of the explosive charge is sufficiently large to provide planar detonation wave.

The DSM theory is one of the most commonly used theories for the penetrative capability of cumulative projectiles in analytical codes such as BASC. Its greatest limitation is the inability to accurately determine the U_{min} size, a value of the minimum jet velocity needed to maintain penetration, which is often not constant but varies with the standoff distance and diameter of the explosive charge for a given configuration [8, 13].

Using the program, it is possible to determine the velocity, mass, energy of the primary and secondary jets, the penetration capability of the jets against different barriers, and it offers the possibility of assessing penetration capability depending on the standoff distance.

With a known constant thickness of the liner, it is possible to run the program and enter the required values to obtain the parameters of the shaped charge jet. Since the program requires entering target characteristics, it will be assumed that, through a plate, the penetration is made of homogeneous steel with a density of 7.8 g/cm³. Other values needed for the operation of the program are shown in Table 1. Main parameters of the liner are represented in Figure 2, based on the measurements taken from a training model of the M80 warhead available for academic use.

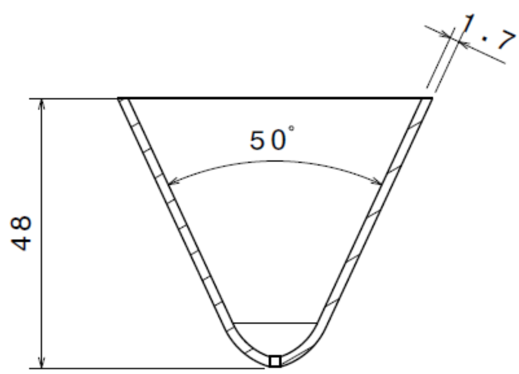

Figure 1. Dimensions of shaped charge liner

Table 1. Parameters for analytical calculation

Parameter	Description	Value	Unit
ALPHA	Semi-angle of the cone of the shaped charge liner	25	○
EPS	Liner thickness	1.7	mm
RHOJ	Liner material density	8.9	g/cm^3
RF	Liner radius	2.83	cm
H	Liner cone height	0	cm
COF	Thickness of warhead case	0.37	cm
RHCON	Case density	2.7	g/cm^3
RHOC	Target material density	7.8	g/cm^3
SO	Standoff distance	20	cm
UMIN	Min. Penetration veloci-ty needed for erosion	450	m/s
T1	Jet breakup time	0	μs
DPOINT	Total length of liner in-cluding deviator and detonator cap	10.5	cm
NEXPL	Explosive charge	5	-

Additionally, when selecting explosive charges, it is possible to choose one of the following explosives: 1 - COMP B, 2 - OCTOL, 3 - TNT, 4 - PBX-9404, 5 - LX14, 6 - O280, 7 - A-IX-1. As previously mentioned, in the 64 mm M80 shaped charge warhead, for the purposes of this work, explosive LX-14 is used, which is the option number 5 in the program [8].

Results after the calculation are represented in Table 2.

Table 2. Analytical calculation results related to various explosive materials

Explosive type	Primary jet mass [g]	Secondary jet mass [g]	Velocity of jet tip [km/s]	Penetration depth [mm]
COMP-B	33.14	55.66	6.78	241.03
OCTOL	33.05	55.75	7.14	278.28
TNT	33.35	55.44	5.97	166.93
PBX-9404	32.99	55.81	7.37	305.46
LX-14	32.99	55.8	7.34	303.52
O280	33.05	55.75	7.14	278.17
A-IX-1	33.11	55.69	6.91	256.65

Numerical simulation

Analytical methods, known for their simplicity of use, provide only a rough approximation of the sought parameters and values. On the other hand, numerical models, which are much more complex, allow a deeper insight into the physics related to the formation and movement of shaped charge jets and provide more accurate results. Considering these characteristics of the numerical approach, it is clear that their use can lead to a significant reduction in costs of the experiments and optimize the warhead [14]. Due to these differences, results obtained from the analytical methods serve as a starting basis in the process of designing and developing weapons and ammunition, while numerical simulations are used in all subsequent steps [15].

The idea behind the development and use of numerical simulations is to save time and resources needed for the real experiments and to create a database that can be used in practice, as well as for development and new research. Simulations save time and money and increase work efficiency. Of course, for a simulation to be considered valid, it must be confirmed by the experiment. There is no available detailed report of determination of Zolja's jet velocity, just the result used for validation, obtained by experiment and provided in [2]. To ensure the validity of the numerical model, the same simulation settings (models, parameters, and material definitions) were first applied to a shaped charge configuration from a published study [16] that includes the experimental results. After successfully reproducing the results reported in that study, the validated settings were then used for the 64 mm M80 warhead simulation.

In this paper, the commercial engineering software ANSYS (ANSYS Academic Research, Release 17.2., ANSYS Inc., Canonsburg, PA, USA) was used for numerical simulations. It is a software that, depending on the module used, operates on the principle of finite element method, finite volume method, or finite difference method, and as a commercial software, it is often used for shape charge jet analysis [17-21]. Through its so-called "Workbench," it combines different subprograms intended for analyzing electronics and assemblies, machine elements and assemblies by analyzing their strength, hardness, elasticity, fluid flow, etc. [22]. For the specific issue of this work, ANSYS Autodyn was used. This module is designed for efficient and high-quality simulation of high-energy density, high strain rate processes involving explosions and large deformations. Through its model database, Autodyn is capable of describing many complex physical phenomena involving the interaction of different aggregate states, phases of material transition from one aggregate state to another, and even the propagation of shock waves. The software developer describes this module as particularly effective for solving all types of problems involving explosive materials. Furthermore, Autodyn is also widely used in non-defense applications, particularly in areas such as car crash simulations, etc. [22].

In the software used, the explosive was simulated using the Strong Explosive Burning model along with the Jones-Wilkins-Lee equation of state, which controls the release of chemical energy [23]. The standard form of the equation [24] is given as follows:

$$P = A\left(1-\frac{\omega}{R_1}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where P is the pressure, A, B, R_1, R_2, and ω are the JWL coefficients (characteristics of high explosives), V is the relative volume, and E is the specific energy.

After creating a 3D model of the warhead in the CATIA software, it is necessary to assign materials to the elements that will be used in the simulation within Ansys. In order for the simulation to be reproducible, it is essential to display all parameters of the materials used. Regarding the materials for the warhead body (Al 6061-T6) and the copper shaped charge liner with a purity of 99.9%, their properties are presented in Table 3.

Table 3. Properties of metal materials used in simulation

	Al 6061-T6	Copper
Density [kg/m^3]	2703	8900
Specific Heat [J/kgK]	885	385
Initial Yield Stress Y [Pa]	$2.9 \cdot 10^8$	N/A
Maximum Yield Stress Ymax [Pa]	$6.8 \cdot 10^8$	N/A
Hardening Constant B [MPa]	125	N/A
Hardening Exponent N	0.1	N/A
Melting Temperature [C]	946.85	N/A
Shear Modulus [Pa]	2.76 · 10	4.64 · 10
Gruneisen Coefficient	N/A	2

Regarding the explosive materials, their characteristics are presented in Table 4.

Table 2. Parameters of JWL EOS for explosives

	HMX	LX-14-0	PBX 9404	OCTOL (HMX 70/TNT 30)
Density [kg/m³]	1891	1835	1840	1776
Parameter A [Pa]	$7.782 \cdot 10^{11}$	$8.261 \cdot 10^{11}$	$8.524 \cdot 10^{11}$	$7.008 \cdot 10^{11}$
Parameter B [Pa]	$7.0714 \cdot 10^{9}$	$1.724 \cdot 10^{10}$	$1.802 \cdot 10^{10}$	$1.211 \cdot 10^{10}$
Parameter R1	4.2	4.55	4.6	4.5
Parameter R2	1	1.32	1.3	1.1
Parameter W	0.3	0.38	0.38	0.3
C-J Detonation velocity [m/s]	9110	8800	8800	8210
C-J energy/mass unit [J/kg]	$5.553 \cdot 10^{6}$	$5.559 \cdot 10^{6}$	$5.543 \cdot 10^{6}$	$5.011 \cdot 10^{6}$
C-J Pressure [Pa]	$4.2 \cdot 10^{10}$	$3.7 \cdot 10^{10}$	$3.7 \cdot 10^{10}$	$3.1 \cdot 10^{10}$

Due to the simplicity of the model and the limited availability of technical data for the Zolja system, the warhead body was approximated with a 1 mm thick aluminum casing, based on external dimensions. The internal wave shaper (deviator) was not explicitly included in the model geometry. However, a simulation was performed in which polyethylene was assigned to the region where the deviator would typically be located. The results showed no significant deviations in jet velocity, and therefore, the deviator was excluded in the final simulations. The aim was to isolate and compare the effect of different explosive materials under consistent boundary and initiation conditions, which included central axial initiation. For numerical simulations in which the formation of a jet and its penetration are evaluated, the role of the deviator is very important because the deviator defines the angles at which the detonation wave encounters the metal liner. It is known that detonation waves move in a spherical shape [25]. According to the classical theory, liner elements are considered to immediately reach the collapse velocity. In numerical simulations, this occurs gradually [26]. Due to the symmetry of the model, the type of analysis is 2D. One of the basic settings that must be emphasized is the creation of a computational grid. Since in this case there are quite thin elements, the grid reduction option was selected and a value of 0.5 mm per square in the grid was used. In Autodyn, a combination of Euler (complete domain, i.e. the space of the jet) and Lagrange mesh (individual elements of the assembly) was used. The model geometry in Autodyn is given in Figure 3.

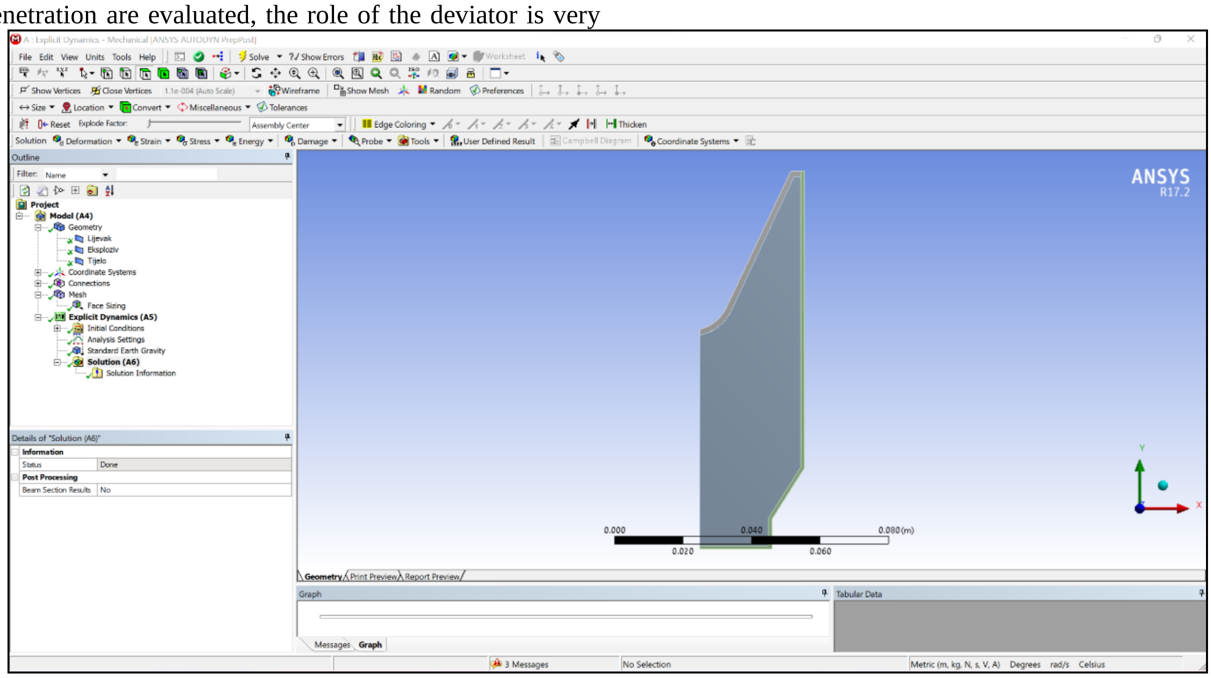

Figure 2. Geometry of the model in ANSYS Autodyn

The boundary condition is defined as a flow out for the complete network in order to prevent wave reflection in the propagation phase. A void (empty space) was used instead of air to eliminate the influence of external medium on jet formation and propagation. Since the focus was on comparing the effects of different explosive materials under identical conditions, the surrounding environment was kept constant and simplified. A realistic value of 200 mm was chosen for the standoff distance. The detonation point was placed on the central axis, 3 mm from the bottom of the projectile, to ensure symmetric jet formation and enable direct comparison between different explosive materials.

The effect of a wave shaper was not included in this study, as the focus was on isolating the influence of explosive type under uniform initiation conditions. Future work may incorporate off-axis initiation to simulate the effect of a wave shaper on jet coherence and velocity. The time step factor is 0.6, and the time increment is 0.1 µs.

Before starting the calculations, it is desirable to validate the parameters. In this case, it was done in such a way that the parameters that were used in the model that was previously experimentally confirmed in the work [16] were used. After the design of an identical model as used in the aforementioned paper, the explosive material RDX, with the following parameters (Table 5), was inserted into the Engineering data module.

Table 3. Properties of RDX

RDX	
Density [kg/m^3]	1700
Parameter A [Pa]	$5.811 \cdot 10^{11}$
Parameter B [Pa]	$6.8 \cdot 10^{9}$
Parameter R1	4.1
Parameter R2	1
Parameter W	0.1
C-J Detonation velocity [m/s]	8390
C-J energy/mass unit [J/kg]	$5.559 \cdot 10^{6}$
C-J Pressure [Pa]	$3 \cdot 10$

The shaped charge liner is made of copper. The value of the jet velocity obtained in the method used by the authors of the model [16] is 6301 m/s, while the value obtained based on the parameters used in this paper is 6307 m/s (Figure 5). Since validation for a specific warhead is not possible due to unavailability of exact experimental data, the results could be considered correct based on parameter validation, provided everything else was done correctly. Figure 4 shows the model that was used in [16].

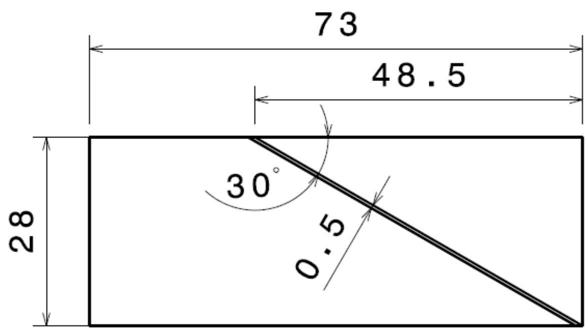

Figure 4. Warhead model used for validation

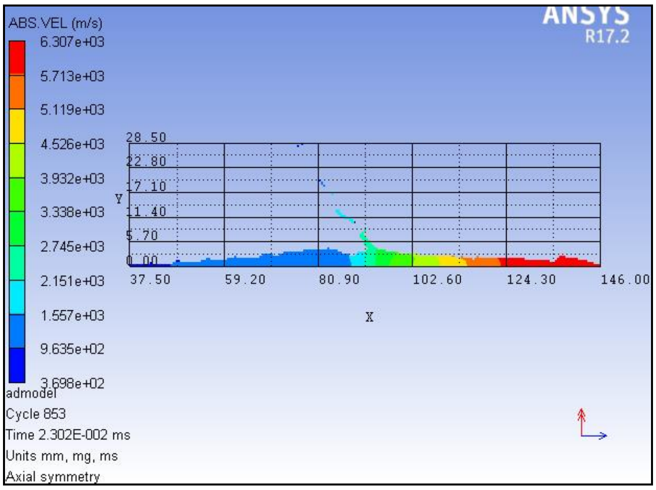

Figure 3. Results of validation

Authors studying the phenomenon of shaped charge jet formation, in [27], agree that this is still a somewhat unresolved topic and a process that cannot be entirely precisely predicted, even with complex physics-based models. Because of this, the use of numerical simulations as a tool for predicting the formation of cumulative jets is an excellent approach that greatly contributes to a better understanding of the phenomenon. It has also been established that the method of manufacturing the shaped charge liner plays a significant role in practice (impact on the jet break, etc.), and it has been defined that, in addition to the speed of the jet and the density of the material, the speed of sound in the liner material is very important when it comes to formation of the jet and its penetration through the target [27].

Thus, in addition to the aforementioned parameters, when selecting the liner material, attention must also be paid to other parameters such as the ductility of the liner material, data on the length of the continous jet, and several others. Taking into account the previously mentioned theoretical assumptions, Held, through his research and various experiments, selected tungsten as the best material for making the liner, followed by molybdenum [27].

The process of simulating the formation of a jet for the combination that uses an aluminum alloy casing, HMX explosive charge, and copper liner at a standoff distance (200 mm) is depicted in Figure 6.

Based on the presented images, many parameters of the jet can be determined in each saved cycle. In this specific case, it is possible to read the speed of the jet from the color scale, the number of cycles shown, and the time in which the displayed cycle occurs. In the coordinate system, the spatial displacement of the jet (x-axis) and its thickness (y-axis) are read. In this case, it is evident that there is a stagnanion point in the jet, such that the primary jet carries about 30% of the material while the secondary jet carries 70% of liner mass.

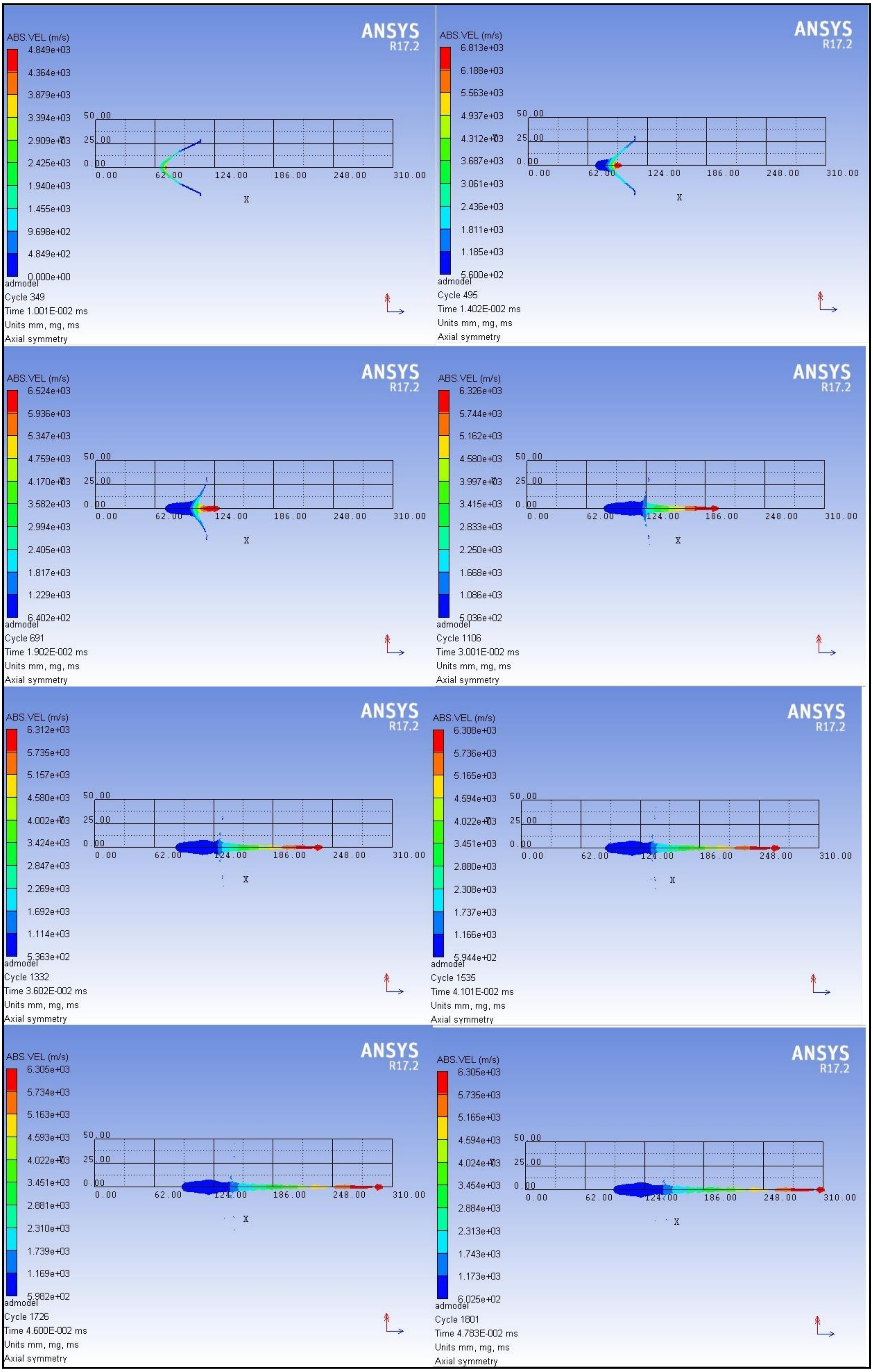

Figure 6. Evolution of shaped charge jet formation - characteristic moments: 10 ms, 14 ms, 19 ms, 30 ms, 36 ms, 41 ms, 45 ms and 47 ms

Jet tip velocity values at standoff distance for different explosives are represented in Table 6.

Table 4. Jet tip velocities for different explosives used

HMX	LX-14-0	PBX 9404	OCTOL
6305 m/s	6265 m/s	6285 m/s	5710 m/s

Although HMX was included in the analysis, it was used solely as a theoretical reference to illustrate the influence of explosive parameters, primarily detonation velocity and density, on the jet formation process. Its inclusion serves to establish an upper performance boundary under ideal conditions, providing a benchmark for comparison with more practical materials.

However, it is well established that pure HMX is not used in shaped charge warheads such as the M80 Zolja, primarily due to its high sensitivity to impact, friction, and heat, as well as its poor castability and processing limitations. In real-world applications, HMX is typically phlegmatized or incorporated into plastic-bonded formulations such as PBX-9404 or LX-14, or mixed with TNT in compositions like Octol (70/30), precisely to balance performance with safety, stability, and manufacturability [28, 29].

Therefore, while HMX provides the highest simulated jet velocity (~6305 m/s), the results for PBX-9404, LX-14, and Octol, which yield slightly lower velocities in the range of 5710 - 6285 m/s, are far more representative of operational conditions and reflect the realistic performance envelope of shaped charge explosives used in actual munitions.

Experience and research have shown that the most favorable case would be the use of a highly potent explosive and a liner material such as platinum or tungsten [30, 31]. Such a scenario is not realistic when it comes to Zolja, but also to most rocket systems in general, because it is economically unfounded. It should also be taken into account that Zolja, and even its successor Stršljen, is a design from a time before the use of numerical simulations. As a result, certain geometric and material choices in their design were based on empirical testing and manufacturing constraints rather than on optimized detonation wave shaping or jet formation predicted by simulation tools. This historical context justifies the simplifications applied in the current numerical model and supports the relevance of studying how modern explosives behave within such legacy designs.

Conclusion

Numerical simulations today replace a large number of experiments and thus result in huge financial savings in the development phase, and therefore it is a realistic option to direct more funds into more expensive materials for the rocket. This is just one of the proven benefits of using numerical simulations. Their disadvantage is certainly the inability to avoid experiments and wrong results if there is a deviation of only one parameter, or an error in verification and validation. Also, the use of different models in different simulations may result in certain deviations. For example, the BASC program uses the Pugh, Eichelberger and Rostoker models for the formation of a shaped charge jet, while in Ansys the calculation is based on the JWL and other material models (the difference occurs up to 1000 m/s). PER as a physically based jet formation model uses a large number of assumptions, while JWL is essentially only a material behavior model. In addition, BASC also makes certain approximations when it comes to material parameters and finite elements. Using the example of a 64 mm rocket warhead, a significant difference in the velocity of the cumulative jet obtained by analytical and numerical methods has been found. In addition, a moderate influence of several contemporary types of explosives on this velocity is identified.

With regard to the explosives, the paper does not suggest a single optimal formulation but rather highlights the importance of selecting compositions that are both economically justified and technically feasible to process, especially when upgrading legacy systems such as the M80 warhead. The focus of this research was to establish a comprehensive method for analyzing jet formation velocity through numerical simulation, providing a reliable framework that can significantly reduce the number of physical tests during the development of new or modernized warheads. In the next phase, the authors will extend the research toward a deeper investigation of the relationship between explosive characteristics and penetration performance, which is expected to contribute to a better understanding and improved design capabilities.

References

[1] Ahmed, M., Malik, A.Q.: A Review of Works on Shaped Charges, Engineering, Technology & Applied Science Research. 7, 5 (Oct. 2017), pp. 2098–2103.

[2] Pravilo: Ručni raketni bacač 64 mm M80, Beograd, Savezni sekretarijat za narodnu odbranu, 1982.

[3] Lukić–Anđelković, M.: Fizičko-hemijske i detonacijske karakteristike nitroaminskih eksploziva – RDX, HMX i CL-20. Vojnotehnički Glasnik 2002, 50(2), pp. 135–146.

[4] Hoffman, D.M.: Fatigue of LX-14 and LX-19 plastic bonded explosives, Lawrence Livermore National Library, 1998.

[5] Humphrey, J.: LX-14 a new plastic-bonded explosive, Lawrence Livermore Laboratory, 1977.

[6] U.S. Department of the Army, Military Explosives, TM 9-1300-214, Washington, D.C.: Headquarters, Department of the Army, 1991.

[7] Research and Development of Material, Engineering Design Handbook, Warheads-General, US Army Materiel command, Washington, 1964.

[8] Harrison T., John.: Improved analytical shaped charge code: BASC, US Army Research and Development Command, 1981.

[9] Pugh, E. M., Eichelberger, R.J., Rostoker, N.: Theory of Jet Formation by Charges with Lined Conical Cavities, Journal of Applied Physics, Vol. 23, Issue 5, 1952.

[10] Tate, A.: A theory for the deceleration of long rods after impact, Journal of the Mechanics and Physics of Solids, Vol. 15, Issue 6, 1967.

[11] Di Persio, R., Simon, J., Merendino, A.B.: Penetration of shaped-charge jets into metallic targets, BRL Report No 1296, 1965.

[12] Birkhoff, G., Macdougall, D.P., Pugh, E.M., Taylor, G.: Explosives with lined cavities. J. Appl.Phys. 1948, 19, pp. 563-582.

[13] Čišić, A. Vojna enciklopedija: Vol. 5; Redakcija Vojne enciklopedije: Beograd, 1974; pp. 110–115.

[14] Elek, P., Jaramaz, S., Micković, D., Miloradović, N.: Numerical Simulation of Fragmentation Warhead Mechanisms, 6th International Scientific Conference on Defensive Technologies OTEH 2014, Belgrade, 9-10 October 2014.

[15] Marković, M., Elek, P., Jaramaz, S., Milinović, M., Micković, D.: Numerical and Analytical Approach to the Modeling of Explosively Formed Projectiles, 6th International Scientific Conference on Defensive Technologies OTEH 2014, Belgrade, 9-10 October 2014.

[16] Kemmoukhe, H., Burzić, Z., Savić, S.,Terzić, S., Simić, D., Lisov, M.: Improvement of Shaped Charge Penetration Capability and Disturbation of the Jet by Explosive Reactive Armour, Tehnički vjesnik, Vol. 26 No. 6, 2019.

[17] Agu, H.O., Hameed, A., Appleby-Thomas, G.J.: Application of Shell Jetting Analysis to Determine the Location of the Virtual Origin in Shaped Charges. Int. J. Impact Eng. 2018, 122, pp. 175–181. https://doi.org/10.1016/j.ijimpeng.2018.04.014.

[18] Ugrčić, M., Ugrčić, D.: FEM Techniques in Shaped Charge Simulation. Sci. Tech. Rev. 2009, 59(1).

[19] Shixin Ma, Xiangdong Li: Numerical study on the damage of liquid-filled containers subjected to shaped charge jet impact. J. Appl. Phys.

28 April 2024; 135 (16): 164901. https://doi.org/10.1063/5.0196346

[20] Sy, N.T., Beer, S., Bien, V.V.: Simulation Study of Shaped Charge Collapse Process and Optimal Standoff Determination. In Proceedings of the International Conference on Military Technologies (ICMT 2019), Brno, Czech Republic, 30–31 May 2019.

[21] Jiang, K., Deng, S.-C., Li, H.-B.: Theoretical Calculation and Analysis of the Velocity of Shaped Charge Jet with Modified Collapse Velocity Model. Petroleum Science 2024, 21(6), pp. 4311–4327. https://doi.org/10.1016/j.petsci.2024.06.017

[22] https://www.ansys.com/products/structures/ansys-autodyn, last accessed: June 6th, 2024.

[23] Downes, D., Bouamoul, A., Nsan, M.: Numerical Simulation of the Shaped Charge, Defence Research and Development, 2014.

[24] Lee L. H., Kury, W.: Adiabatic expansion of high explosive detonation products, Lawrence Radiation Laboratory, 1968.

[25] Marković, M., Elek, P., Jevtić, D., Đurović R., Todić, I.: Numerical Analysis of the Inhomogenous Obstacle Influence on the Precursor Shaped Charge Warhead Performance, 10th International Scientific Conference on Defensive Technologies OTEH 2022, Belgrade, 13-14 October 2022.

[26] Micković, D., Elek, P.: A Model for Shaped Charge Warhead Design. Strojniški Vestnik – Journal of Mechanical Engineering 2012, 58(6), pp. 403–410, https://doi.org/10.5545/sv-jme.2012.335

[27] Held, M.: Liners For Shaped Charges, Journal of Battlefield Technology, Vol. 4, No. 3, 2001.

[28] He, Z.H., Huang, Y.Y., Ji, G.F., Chen, J., Wu, Q.: Anisotropic Reaction Properties for Different HMX/HTPB Composites: A Theoretical Study of Shock Decomposition. Molecules 2022, 27(9), 2787. https://doi.org/10.3390/molecules27092787

[29] Lin, C., Gong, F., Yang, Z., Zhao, X., Li, Y., Zeng, C., Li, J., Guo, S.: Core-Shell Structured HMX@Polydopamine Energetic Microspheres: Synergistically Enhanced Mechanical, Thermal, and Safety Performances. Polymers 2019, 11, 568. https://doi.org/10.3390/polym11030568

[30] Zaki S., Uddin E., Rashid B., Mubashar A., Shah S. R.: Effect of liner material and explosive type on penetration effectiveness of shaped charge. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 2018;233(7): pp. 1375-1383. doi:10.1177/1464420717753233

[31] Zhang, X., Wu, C. & Huang, F.: Penetration of shaped charge jets with tungsten–copper and copper liners at the same explosive-to-liner mass ratio into water. Shock Waves 20, pp. 263–267 (2010). https://doi.org/10.1007/s00193-010-0248-0

Received: 25.03.2025.
Accepted: 01.06.2025.

Proračunska studija uticaja vrste eksploziva na brzinu kumulativnog mlaza bojne glave kalibra 64 mm

Konstantan razvoj zaštitnih materijala i oklopnih sistema zahteva i stalna unapređenja na polju razvoja protivoklopne municije. Jedna od najčešće korišćenih grupa ove municije su kumulativni projektili. Srbija je decenijama svetski priznata u proizvodnji kvalitetnih ručnih raketnih bacača opremljenih različitim kalibrima kumulativne municije. Jedan od najpoznatijih predstavnika je ručni bacač raketa kalibra 64 mm M80, poznatiji pod nazivom „Zolja”. Iako je decenijama u upotrebi i nema potrebne osobine za dejstvo protiv modernijih sistema zaštite, zadržavanjem tradicionalnog dizajna i odavno usvojenih proizvodnih tehnologija, zajedno sa upotrebom potentnijeg i modernijeg eksploziva, moglo bi se značajno dobiti na njegovoj probojnoj moći. Ovaj rad upotrebom analitičkog proračuna i numeričkih simulacija analizira kako različite eksplozivne materije utiču na brzinu formiranja kumulativnog mlaza iz kumulativnog eksplozivnog punjenja bojeve glave 64 mm M80, što direktno utiče na njene sposobnosti penetracije.

Ključne reči: **kumulativna bojeva glava, brzina mlaza, penetracija, numerička simulacija, eksploziv**