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*Research paper*

## Influence of Liner Form and Explosive on the Velocity and Mechanical Action of a Shaped-Charge Jet

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**Abstract:** The results of modeling the operation of shaped charges with conical, biconical, and elliptical liners and various detonation initiation schemes are presented. A comparison of the modeling results with data from experimental studies conducted on charge models and with the results of modeling by other authors has been carried out. A dependence of the leading part velocity of the copper shaped-charge jet for copper liners with apex angles of 44-50° on the parameter  $\rho D^2$  in the low detonation velocity ( $D$ ) and explosive density ( $\rho$ ) range, is proposed.

**Keywords:** shaped charge, liner, shaped-charge jets, penetration

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## 1 Introduction

Various methods are used to penetrate solid barriers. A traditional method involves the use of shaped charges with conical liners. A brief overview and analysis of recent works in the field of these show that, in addition to the explosion energy and detonation velocity ( $D$ ), the mass-kinetic parameters of the shaped-charge jet are significantly influenced by the shape and material of the liner, as well as the method of initiation. The review of publications presented in [1, 2] will be supplemented by several articles not mentioned or analyzed in [2]. The most significant research results are presented in [1-9]. Publications [3-6] illustrate the experimental and theoretical impact of liner shapes differing from classical conical and spherical liners. In [4], one such shape is bi-apex-angle. In [3], a similar shape is termed elliptical. Both studies, [3, 4], demonstrate that liners of such shapes increase the penetration depth of copper-shaped charges into concrete and steel concrete by approximately 25-40% [3]. Zirconium-shaped charges with flared liners increase this by 10.3%, whereas the increase for biconical liners in a combined barrier of “steel A-36-water-steel A-36-concrete” is 22% [3].

Experimental data regarding penetration depth into 40 MPa strength concrete for high-purity zirconium-shaped charges with hemispherical, conical, bell-shaped, and bi-apex-angle liners are 48.4, 68, 75 and 83 cm, respectively [4].

The properties of explosives and liner materials are as follows:

- in [3]: phlegmatized hexogen (RDX) with a density ( $\rho$ ) of 1650 kg/m<sup>3</sup> and  $D$  of  $\sim$  8200 m/s; copper with  $\rho$  of 8900 kg/m<sup>3</sup> (monolith) and 8400 kg/m<sup>3</sup> (porous with powder; relative porosity  $\approx$  1.06 and absolute porosity is 5.6%),
- in [4]: explosive composition RE4 based on RDX (88% RDX and 12% plasticizer and other additives) with  $D = 8027$  m/s at  $\rho = 1600$  kg/m<sup>3</sup> and the charge caliber of approximately 40 mm.

It is also worth noting the improvement in the efficiency of a shaped charge with a semi-spherical liner of regressive thickness [5]. As analysis of the collapse process showed, the mass-kinetic parameters of the shaped-charge jet approach the level of parameters of the shaped-charge jet from collapsing conical liners, and may even exceed them with liner shape optimization. However, this optimism is not shared by the authors of [6], who, using their calculation methodology,

demonstrated that in the presence of drift (lateral component of velocity  $V_r$ ), the mass-kinetic parameters of the shaped-charge jet, as well as the penetration depth, lag behind the parameters of a shaped-charge when collapsing a conical liner. Moreover, this lag increases with the magnitude of the drift. There is an approximation to corresponding parameters for an ideally symmetrical shaped-charge jet. The magnitude of the drift, in turn, depends on technological inaccuracies in charge manufacturing. According to [6], the enhancement of penetrating ability should focus on achieving the maximum possible length of the shaped-charge jet and optimizing the mass-velocity distribution of the material along the shaped-charge jet.

The effectiveness of liners with curvilinear shapes, characterized by a gradual increase in the angle from the apex to the base and a gradual increase in thickness from the apex to the base, was researched in [7]. Compared with a conical liner with an angle of  $2\alpha = 60^\circ$  at the apex, liners with curvilinear surfaces allow for an increase in the velocity of the shaped-charge jet and, at a specific curvature value, also increase the penetration depth. Increasing the thickness of the liners for all the shapes investigated in the study (conical and two variants of liners with curvilinear surfaces) showed an increase in the velocity and penetration depth into RHA steel targets.

The conical liner with a constant thickness (225 mm) exhibited the smallest penetration depth, and the liner with a smaller angle at the apex of  $2\alpha = 40^\circ$  and a curvilinear surface (255 mm), showed the highest penetration depth. Charges with bi-apex-angle liners were researched in [8, 9]. In [8], a linear-shaped charge was examined, including a bi-apex-angle one with angles of  $40^\circ$  at the apex and  $60^\circ$  near the base of the cone. In [9], a charge with axial symmetry and angles at the liner's apex and base of  $38^\circ$  and  $60^\circ$ , respectively, was investigated. The authors of [8] demonstrated that the bi-apex-angle liner increases the velocity of the shaped-charge jet and penetration depth by 29.72% compared to the standard angle of  $60^\circ$  at the apex. Reducing the liner thickness from 1.2 to 0.4 mm resulted in approximately a threefold increase in penetration depth. Overall, the results highlighted in [2-4, 7-11] indicate that the optimal angle at the liner's apex and its thickness ensure the maximum velocity of the front part of the shaped-charge jet and penetration depth into barriers.

In technical applications, there is often a need to increase the barrier effect of a charge. In such cases, changes are made to the liner material, for example, using Al instead of Cu [12] or altering the liner shape to form an explosively formed penetrator instead of a shaped-charge jet.

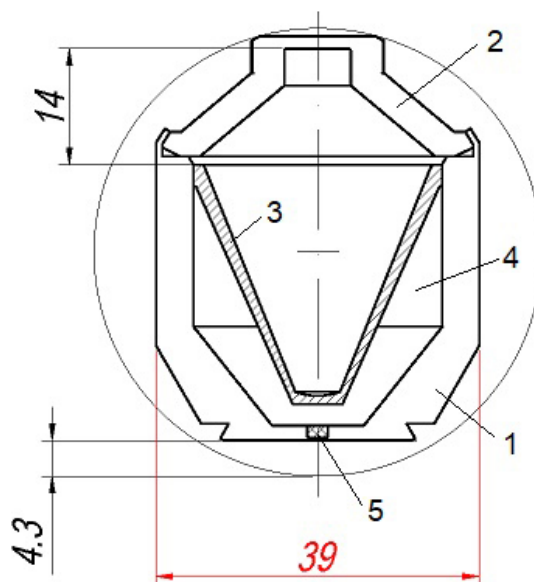
A similar charge was studied in [13]. The explosive and composition were the same (70 RDX/30 TNT), with a charge caliber of 56 mm. The thickness of

the conical liner with an apex angle of approximately  $58\text{--}60^\circ$  was 1.16 mm. The detonation scheme involved initiation from the center, originating from a point on the axis of symmetry. According to X-rays, the velocity of the front and rear parts of the shaped-charge jet was 6.7 and 1.2 km/s, respectively. The diameter of the shaped-charge jet was 2 and 14 mm, respectively, 30  $\mu\text{s}$  after detonation.

This paper compares experimental data obtained from shaped charges with conical and semi-elliptical liners with similar results from numerical simulations.

## 2 Materials and Methods

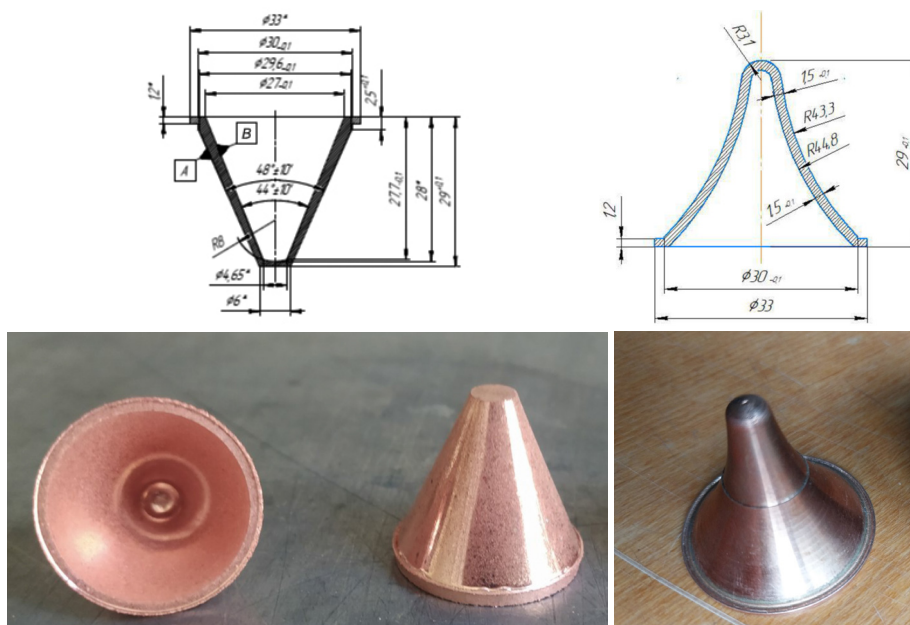
To experimentally research the influence of different liner shapes, a 30 mm caliber charge model with a strip-type shaped-charge perforators was used (Figure 1). The diameter of the described circle is 54 mm. Conical and elliptical liner shapes were studied in the experimental charges (Figure 2). Conical liners were manufactured using the method of one-sided cold pressing from PMS-N powder. Elliptical liners were made from monolithic M1 copper on a numerically controlled lathe (CNC). The liner thickness was 1.2 mm in one version and 1.7 mm in another. The metallographic structure of the liner material had a grain size of 15-45  $\mu\text{m}$ .



**Figure 1.** Design of charge: 1 – body, 2 – lid, 3 – liner, 4 – explosive checker and 5 – intermediate detonator

A mixture of TG-30/70 (30% TNT and 70% RDX and  $D = 7.8$  km/s) was used as the explosive. The charge was prepared by pouring molten TG-30/70, heated to the melting temperature of TNT ( $>80$  °C), into the hole in the casing from the apex side of the liner. The detonation was initiated by an electric detonator through an extended charge of phlegmatized RDX in an aluminum shell with a diameter of 10 mm (Figure 3). The position of the extended charge on the test charge was fixed using a larger caliber charge body 2 (Figure 3).

The overall view of the experimental stand on the target is shown in Figure 3. The necessary distance from the charge to the target was provided by the height of a plastic cylinder, on which the charge and contact sensors from copper foil (under the charge and the cylinder) were placed. The target made of low-carbon steel St.3 consisted of a set of plates with a thickness of 10 mm (Figure 3). The shaped-charge jet speed was measured by the contact sensors method (Figure 4) using a digital oscilloscope IDTM12052CL of the UNI-T company.



**Figure 2.** Designs of conical and elliptical liners



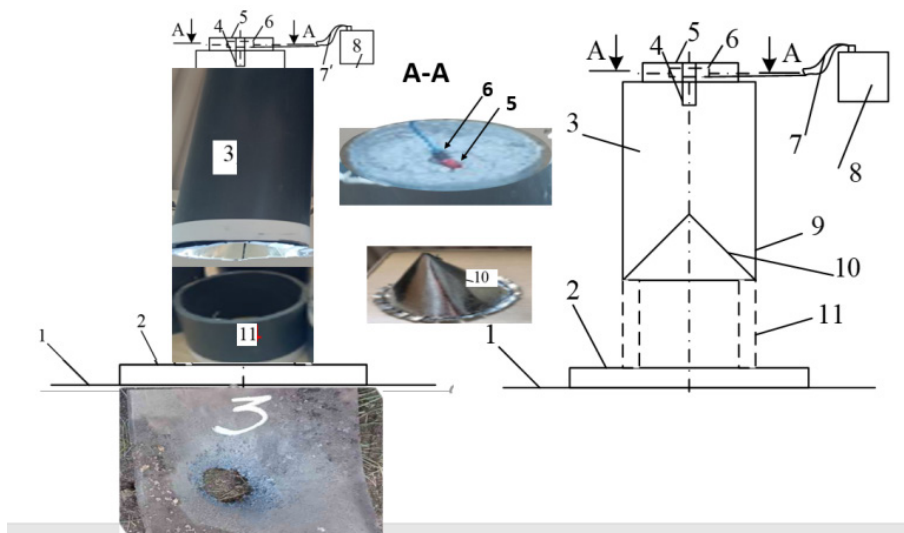


**Figure 3.** General view of the experimental set-up (left) and the target after the shot (right): 1 – target, 2 – charge, 3 – detonating cord, 4 – electric detonator and 5 – plastic cylinder



**Figure 4.** An oscillogram obtained from the shorting of a pair of contact sensors with a shaped-charge jet

Separate experiments were conducted with charges of various explosives based on ammonium nitrate and foamed blasting compositions (FBC) [14] (Figure 5). The density of the explosive after preparation was approximately  $750\text{--}800\text{ kg/m}^3$  and  $D = 1.5\text{--}2.0\text{ km/s}$ . The conical liner was made of low-carbon steel with an apex angle of  $2\alpha = 60^\circ$ . The liner thickness was  $0.4\text{ mm}$ . The detonation was initiated by a detonating cord from the opposite end of the charge. The target was a plate made of St. 3 steel on a soil foundation.



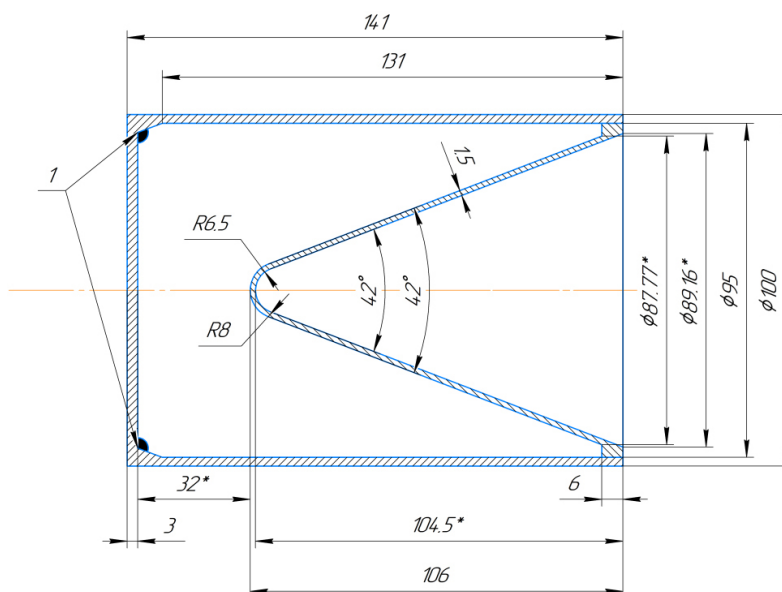
**Figure 5.** FBC charge with a shaped-charge recess and a steel liner on a steel plate (initiation using electric detonator 8-Zh and detonating cord DSH): 1 – ground mass surface, 2 – steel plate, 3 – FBC charge, 4 – LDPE strip with adhesive layer, 5 – DSH cord, 6 – electric detonator 8-Zh, 7 – blasting conduit, 8 – blasting machine, 9 – plastic tube (diameter – 100 mm, height – 300 mm, wall thickness 6 mm), 10 – conical liner and 11 – standoff for setting the required distance

The results of tests with an industrial charge containing a 30 mm caliber liner of progressive thickness and a cone angle of  $44^\circ/48^\circ$  at the apex, were used to compare the shaped-charge jet velocity experimental data [15]. The liner mass was 15 g in one version and 20–22 g in the second. The explosive mass in the charge (pressed phlegmatized RDX) was 18–22 g and  $D$  was  $\approx 8100\text{--}8200\text{ m/s}$ .

### 3 Model of Simulation

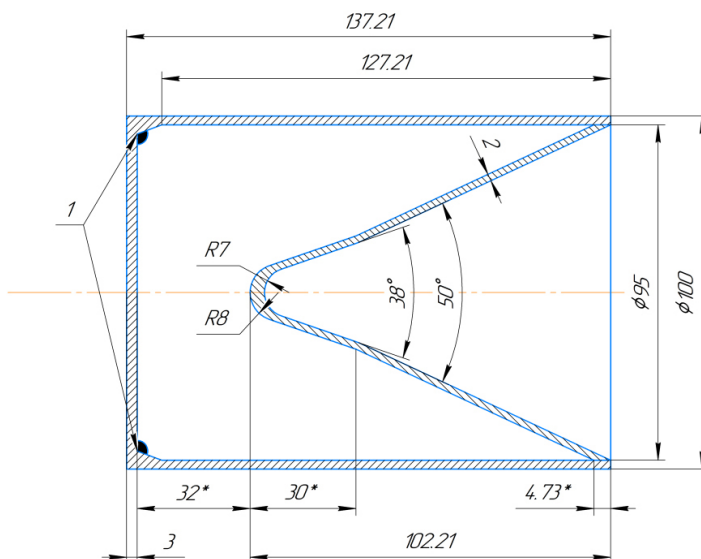
Mathematical studies of the process of shaped charge functioning were carried out in accordance with the method described in [2]. Three structural schemes were considered with a liner in the form:

1. A cone of constant thickness  $\delta = 1.5$  mm with an angle at the top of  $42^\circ$  [2] (Figure 6).
2. A bi-apex-angle shape with angles at the top of  $38^\circ$  and  $35^\circ$  and at the base of  $50^\circ$  of different thickness (1.5, 2.0 and 2.5 mm) (Figure 7).
3. Elliptical shape with a thickness of 2 mm. The detonation excitation scheme is from a point on the axis of symmetry ( $Z$ ) and along a circle ( $R$ ) (Figure 8).

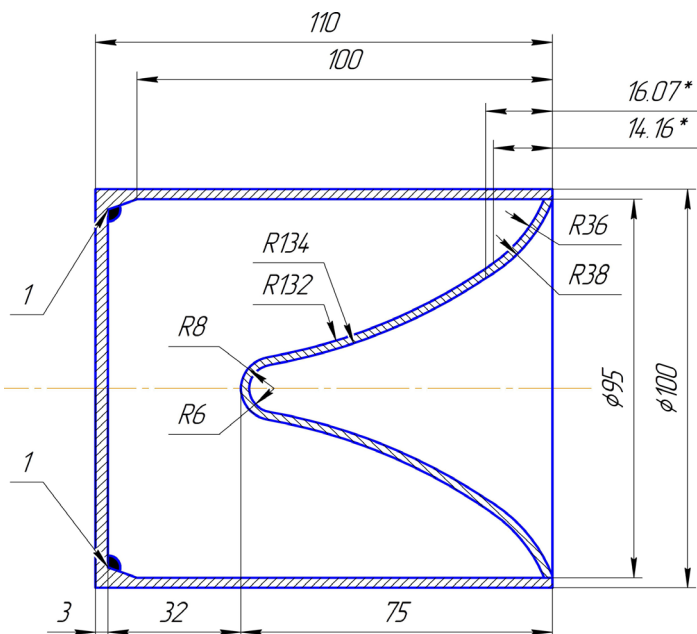


**Figure 6.** Scheme of a shaped charge with a cone liner with an angle at the top of  $42^\circ$





**Figure 7.** Scheme of a shaped charge with a bi-apex-angle liner with angles at the apex of  $38^\circ$  and at the base of  $50^\circ$



**Figure 8.** Scheme of the charge design with an elliptical liner 2 mm thick; detonation excitation scheme – R

The main features of the computational schemes of shaped charges in Figures 5-8 is that:

- The constructions have a cylindrical body with a wall thickness of 3 mm and a closed bottom.
- The diameter of the outer surface of the charge body is 100 mm.
- The distance from the inner end surface of the charge body to the liner is 32 mm.
- There is a charge of explosive (64% RDX and 36% TNT) inside the body. It is an explosive mixture with  $\rho = 1660 \text{ kg/m}^3$  and  $D = 8000 \text{ m/s}$ , which, in its energetic characteristics, is a close analog to phlegmatized RDX ( $\rho = 1.67 \text{ g/cm}^3$ ,  $D = 8100 \text{ m/s}$ ).
- They have axial symmetry, allowing for numerical modeling of the functioning process in a two-dimensional axisymmetric setting.

Modeling of various methods of initiation of the explosive charge was carried out by inserting the corresponding initiation point in the computational models: either at the center on the axis of symmetry near the inner end surface of the charge body (*i.e.* in the absence of the explosive lens,  $Z$ ), or in a circular pattern on the outer end surface of the charge body (*i.e.* in the presence of the explosive lens,  $R$ ). This was done by locating the respective initiation points on the axis of symmetry – point 2 (without the lens, not shown in the figure) and point 1 (with the lens), positioned 46 mm away from point 2 toward the inner surface of the charge body.

## 4 Results of the Shaped Charge Jet Free Flight behaviour and Interaction between the Shaped Charge and a Target

A comparison of the calculated results for the elliptical liner (Figure 8) with those of experimental measurements (Table 1) showed their relative closeness. Differences in velocities along the shaped-charge jets for elliptical and conical liners of progressive thickness with apex angles of  $42^\circ/43^\circ$  (Figure 11) [2], favour bi-apex-angle and elliptical liners.

**Table 1.** Test results of ZKM-54-U charges with conical and elliptical liners

No.	Liner material	Mass of liner [g]	$L$ [mm]	$d_1$ [mm]	$V_z$ [m/s]	$F$ [mm]	Liner shape
1	Pressed copper from copper powder	22.48	63.0	10.7	–	21	Conical $2\alpha = 44^\circ/48^\circ$
2		22.01	64.0	10.6	–		
3		22.67	55.0	11.0	–	20	
4		22.31	62.5	10.8	–		
5		22.28	77.5	10.5	–	40	
6		22.32	77.5	10.0	–		
7*		15.12	80-95*	–	6170*	14	
8*		15.01	115-120*	–	–	25	
7	Monolithic copper	21.24	80**	9.0	6029	40	Elliptical
8		21.26	60-61**	8.0	6250		
9		22.53	65-70**	8.5	6349		
10		22.90	100+	6.5x8	–		
11		21.25	100+	7.5	–		
12		23.17	65-70**	8.0	–		

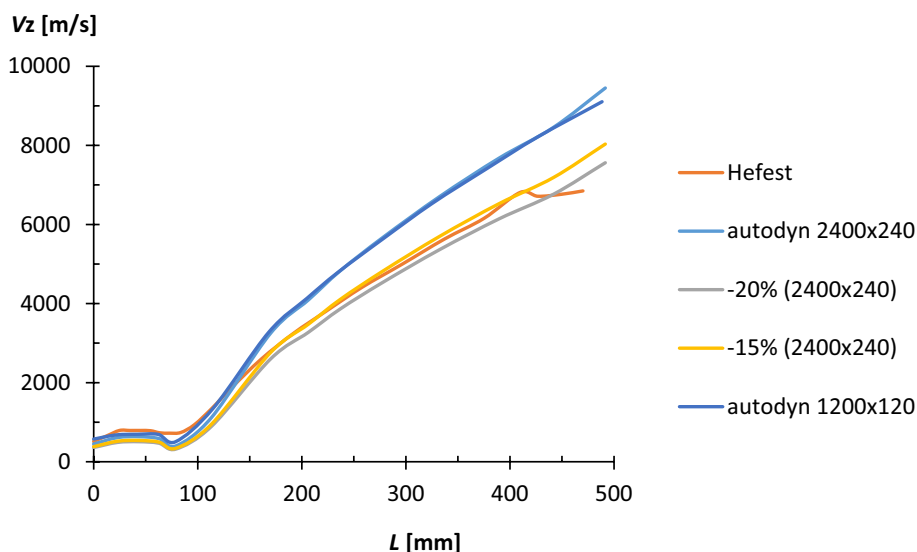
\* Results from [15] for phlegmatized RDX ( $D = 8100$  m/s);

\*\* The tip of the hole is filled with shaped-charge jet material

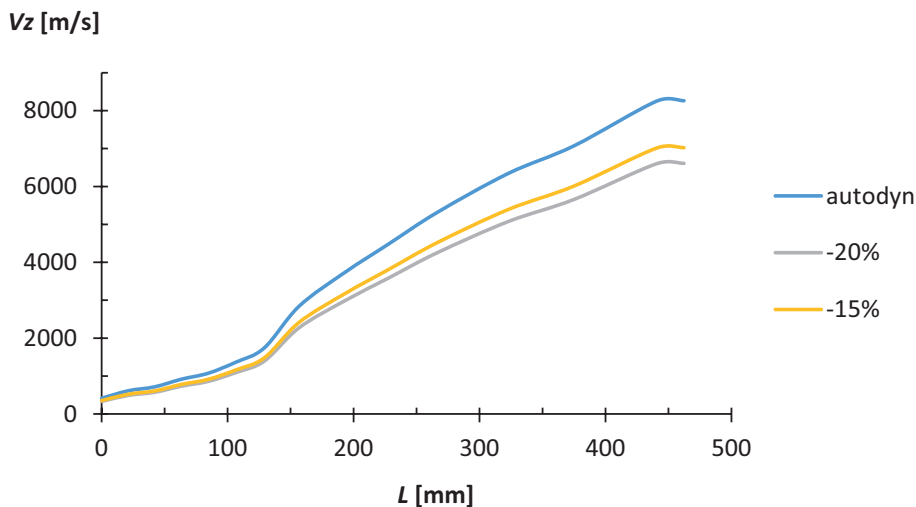
The designations  $Z$  and  $R$  in Figure 11 denote the scheme of charge detonation: from the point on the axis of symmetry ( $Z$ ) and in a circular contour (lens scheme of detonation excitation –  $R$ ). For the elliptical liner, calculations were also conducted for the lens scheme of detonation excitation. Significant scatter of values in the penetration depth of the shaped-charge jet from elliptical liners is not affected by the thickness of the liners (Table 1). One possible reason is the not entirely reliable scheme of detonation excitation with the possibility of forming a thin air gap between charge 3 and the main charge 2 (Figure 3). On the other hand, a scatter in penetration depth for the elliptical liner was also observed by the authors of [3] with another more reliable scheme of detonation initiation. Thus, another reason for the scatter may be technological errors in the manufacturing of the elliptical liners and the lateral drift velocity [6, 13]. This is indicated by the fact that the velocity of the shaped-charge jet and the depth do not depend on the mass of the liner (Table 1). The advantages of this liner shape are explained by the higher velocity of the main part of the shaped-charge jet compared to the shaped-charge jet during the collapse of conical liners with apex angles of  $44^\circ/48^\circ$  (Figure 11, Table 1).

The main results of modeling the operation of charges with different liners are presented in Figures 9-11 and Table 1. The figures show the distribution of the

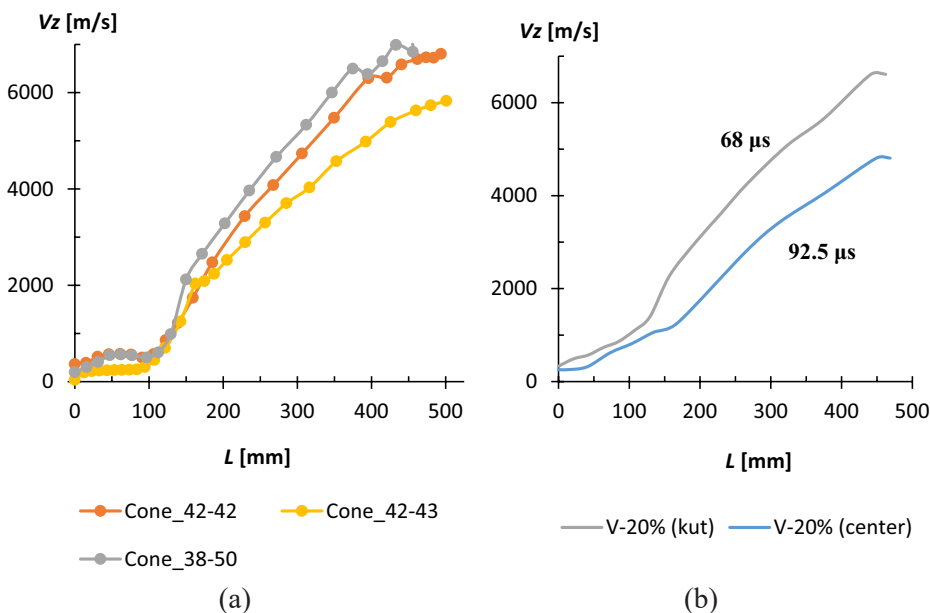
axial velocity of the liner material which has turned into a shaped-charge jet. The shape of these curves shows that the jets formed during the explosions of shape charges with liners of various geometries are high-speed jets of substance with gradients depending on the configuration of the liner. Comparing the results of numerical modeling using two methods, the author's program "Hefest" and the program ANSYS/AUTODYN [2], showed a difference of about 15% (Figure 9). Therefore, for comparison with experimental data, the results of calculations by the "Hefest" program or the ANSYS/AUTODYN program minus 15% were used.



**Figure 9.** Comparison of the results of calculating the distribution of axial velocity values along the shaped-charge jet for a 35-50° liner by different methods (Cu 35-50-1.5 mm)



**Figure 10.** Comparison of the results of calculating the distribution of axial velocity values along the shaped-charge jet for an elliptical liner by different methods



**Figure 11.** Distribution of axial velocity values along the shaped-charge jet for separate parts of the jet (by markers) formed from shaped-charge liners of different shapes

A comparison of the velocity of the main part of the jet with experimental data was conducted using results published in [15-18]. The velocity distribution along the jet in [1] is close to linear, as shown in Figure 11. The influence of  $D$  on the jet velocity is indicated by data from [1, 11, 16-18].

## 5 Discussion of Results of Studying the Shaped Charge Jet Free Flight behaviour and the Interaction between the Shaped Charge and the Target

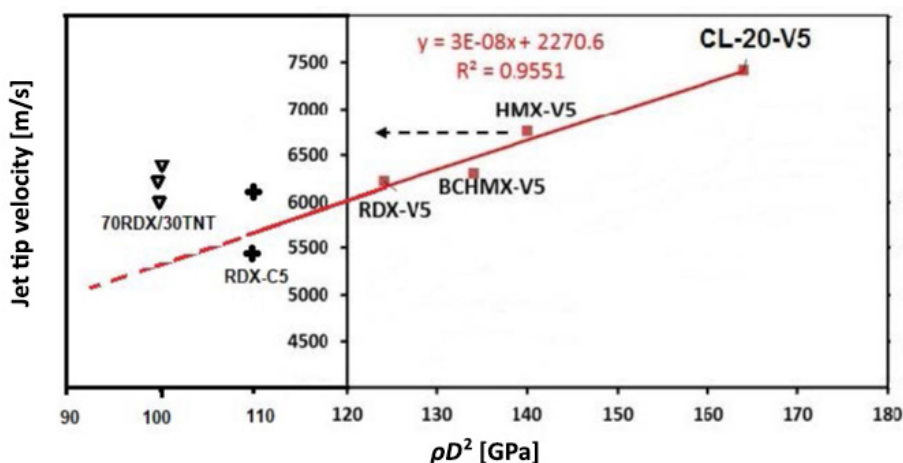
The most similar object to the one under study is a shaped charge investigated in [16]. Liners for small-caliber charges used in this study were made of electrolytic oxygen-free copper with a purity of 99.99% Cu, which has good plasticity with a uniform liner wall thickness of 1.2 mm. The liner had a base diameter of 31.8 mm, a cone angle of  $50^\circ$ , and a height of 27.35 mm. The metallographic structure of the liner material had a grain size of 15-25  $\mu\text{m}$  and a hardness of 55-65 HV5. The charge body was made from a polyethylene cylindrical rod on a CNC lathe. The body had an outer diameter of 34 mm and an inner wall thickness of 2.0 mm. Three different types of plastic-bonded explosives were manufactured based on 95% by weight individual explosive material, bonded with 5% Viton A 200. The research also used hexogen with the same additive quantity as a base explosive. The  $D$  values of these explosives increased from 8424 m/s (RDX-V5) to 8612 m/s (BCHMX-V5), 8730 m/s (HMX-V5) to 9194 m/s (CL-20-V5).

Linear dependencies of the shaped-charge jet velocity  $V_z$  and penetration depth into rolled homogeneous armour (RHA) from the detonation parameter  $\rho D^2$ , which characterizes the detonation pressure, *i.e.*  $\rho$  and  $D$ , were obtained. If the straight line is extended towards smaller values of the  $\rho D^2$  parameter, it can be concluded that at  $\rho D^2 \approx 110$  GPa. The experimental values of  $V_z$  obtained in [15] and in this work, satisfactorily coincide with this (Figure 12).

Some deviation can be explained by the different shapes (extreme points on the left) and the lighter material of the liner ( $\rho \approx 8100$  kg/m<sup>3</sup>, the second group of points from left to right). With an increase and decrease in the value of the  $\rho D^2$  parameter, the dependence will be valid for liners with apex angles  $2\alpha \approx 50^\circ$  and close to this value for other explosives. Thus, for explosives with parameters  $\rho = 800$  kg/m<sup>3</sup> and  $D$  in the range of 1500-2000 m/s, we have  $\rho D^2 = (1.35-2.4)$  GPa. According to [1], the critical penetration velocity of RHA for low-carbon steel is approximately  $\approx 2000$  m/s. Since plate penetration from low-carbon steel was obtained in the experiment (Figure 5), then  $V_z \geq 2000$  m/s. This is explained by the small thickness of the liner (0.4 mm) and its  $\rho$  (7800 kg/m<sup>3</sup>). If this



assumption is valid, then this dependence allows the shaped-charge jet velocity for other types of explosives with a parameter less than 100 GPa and greater than zero, to be estimated. Consequently, this dependence will be useful in practical applications, solving engineering problems when the  $D$  value is 2000-6000 m/s and the explosive  $\rho$  is not more than 1500-1600 kg/m<sup>3</sup>.



**Figure 12.** Dependence of shaped-charge jet speed on detonation speed; to the right of  $\rho D^2 = 120$  GPa [16]; to the left of  $\rho D^2 = 120$  GPa – according to the data presented

The results of numerical experiments have shown that they agree satisfactorily with the data from other authors' studies and experimental results. Additionally, they indicate that further optimization of the shape and thickness of biconical and elliptical liners allows the desired technical outcome, maximum velocity and penetration depth through barriers, to be achieved. The significant difference in the calculated velocity of the shaped-charge jet for the elliptical liner (Figure 12, right part) and the experiments (Table 1) can be explained by the different liner thickness (1.2 and 1.7 mm in the experiment, 2 mm in the calculation), varying casing thickness of the charge, and an imprecise detonation initiation scheme in the experiment: the diameter of the detonation initiation area is 9 mm with a 30 mm charge caliber. An attempt to calculate the performance of a shaped charge with a molybdenum liner proved unsuccessful due to the use of the molybdenum equation of state in the form of Theta  $P(\rho)$  from [1]. This equation of state is valid in the range of 0-50 GPa, and the calculation shows that at the initial stage of formation, the pressure on the axis of the molybdenum-shaped charge exceeds this by approximately 1.5 times (Figure 13).

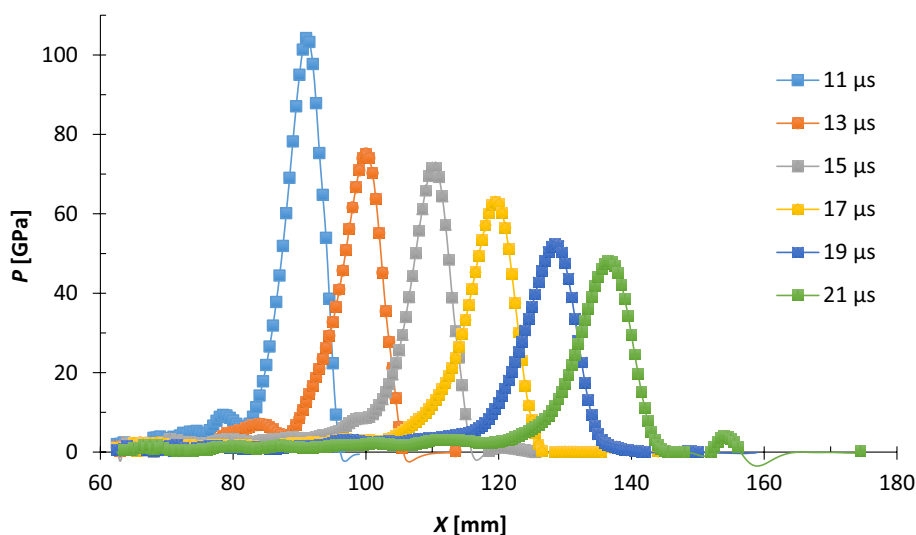


Figure 13. Pressure along the axis of the molybdenum shaped-charge jet

## 6 Conclusions

- ◆ The results of experimental and computational studies are in satisfactory agreement with each other and with known data and can be used to optimize the designs of charges with unconventional liner shapes.
- ◆ The velocity and penetration depth of the barrier during the collapse of semi-elliptical and biconical liners exceed similar parameters during the collapse of conical liners with apex angles of 42-48°.
- ◆ The dependence of the velocity of the main part of the shaped charge for copper liners with apex angles of 44-50° on the parameter  $\rho D^2$  is approximately linear in the range of low detonation velocities  $D$  and explosive densities  $\rho$  and can be used in practical engineering applications.

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### Contribution

- Yuri Voitenko: conception, foundations
- Yuri Sydorenko: conception, performing the experimental part
- Roman Zakusylo: foundations, other contribution to the publication
- Viktor Boyko: foundations, performing statistical analysis
- Olexandr Artemiev: methods, performing statistical analysis
- Volodymyr Bugaiets: performing the experimental part, performing statistical analysis
- Daryna Zakusylo: performing the experimental part, other contribution to the publication

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