The using of the shaped charges for destruction of ice cover

V I Kolpakov¹, N A Kudyukov¹, S V Ladov¹, Ya M Nikolskaya¹ and S V Fedorov¹

¹ Special Machine building department, Bauman Moscow State Technical University, Moscow, Russia

E-mail: sm4-2009@mail.ru

Abstract. The possibility of using cumulative charges for the destruction of the ice cover is considered. On the basis of experimental researches and numerical calculations, the features of the penetration of a cumulative jet into an ice obstacle, as well as the nature of the destruction of ice in the zone of the through hole formed, are analysed. In this case, the existence in the neighborhood of the penetration whole the zones of strength weakened has been established and quantitatively described: zones of fine-dispersed compacted snow-ice, zones of fine-crystalline crushed ice particles and cracking zones. This feature can be used in the development of an appropriate combined explosive device for the destruction of the ice cover.

1. Introduction

At the present time, shaped charges (SC) with metal liners of conical or hemispherical shape find wide application both in the military field and in a number of civil explosive technologies [1–3]. At the same time, the most probable problem is the penetration of classical axisymmetric SC, forming by the high-speed shaped charge jets (SCJ), through the monolithic metal barriers [4, 5].

In engineering methods of estimating the depth of penetration from SCJ in this rigid-plastic barriers, as a rule, a hydrodynamic cumulation model with corresponding correction coefficients is used. The role of such amendments (correction coefficients) is especially increasing in the transition to non-traditional material of barriers, such as rock, concrete, ice, frozen ground, water, which have recently attracted interest because of the possibility of expanding the scope of use of SC.

As a rule, such materials have a low density and a sufficiently high compressibility in relation to, for example, steel. Some of them are characterized by the inertial motion of the environment and the fragile nature of the destruction; in addition to the triggering elements of SCJ, an important contribution to the formation of a cavity can be made by a pestle penetrating like a rigid body [6].

Let us consider the features of penetration of ice barriers under the action of SC on the basis of experimental and numerical researches.

1.1 Some information about ice barriers

It is known that an ice barrier of finite thickness has a substrate in the form of water, however the thickness of ice in itself can be very large and for small SCs it is an barrier of semi-infinite thickness. Ice is rather difficult environment with the characteristics changing depending on surrounding conditions [7]. Semicrystalline ice, which consists of randomly interlocked or intergrown individual crystals, is generally spread. Therefore, when assessing the penetrating power of SCJ with a sufficient degree of accuracy, ice can be considered isotropic.

We will provide data on some physicomechanical characteristics of ice [7]. Density of pure ice at 0 °C is 916,8 kg/m³, sea ice because of existence of a time and impurity 800 … 916 kg/m³. The
module of elasticity changes within 9000 ... 9500 MPa, the shift module – 3000 ... 3400 MPa, Poisson's coefficient – 0.31 ... 0.37. Strength at compression changes in the wide range 0.98 ... 7.85 MPa, at stretching – 0.66 ... 2.75 MPa. Dynamic hardness of ice at decrease in temperature from 0 °C to -25 °C changes from 5 to 8.3 MPa.

It must be said about the heterogeneity of the structure of the intruding ice, which can be layered. As a rule, the basis is crystalline (transparent) ice, which comes from its lower surface, from water, and above it - the so-called cloudy ice (the freezing of wet snow or the freezing of water on the upper surface of the ice cover). The strength of cloudy ice is about 2 times weaker than crystalline ice, but it breaks up under the effect of an explosion more difficult. It is even more difficult to break up layered ice (ice-snow-ice).

All this must be taken into account, first of all, in the calculation methods.

2. Experimental researches

In figure 1 shows the corresponding SC schematic diagrams with a typical explosive charge (EC) form and the shaped charge liners (SCL) that were used in the experiments and calculations.

![Figure 1](image)

**Figure 1.** Constructive schemes SC: a - with conical SCL; b - with hemispherical SCL.

In laboratory experiments has been used SC with copper conical SCL of three scales: diameter 20, 36 and 50 mm, which were "shot" either in a rigid steel pipe, or in a steel ice-filled tank (box) by layerwise freezing of fresh ice by the method of slow crystallization of water under natural conditions at temperatures -5 °C ... -15 °C. The result was a fine-grained hemicrystalline ice without significant contamination with an average density of 905 kg / m³.

In the course of the experiments, the depth of penetration of SCJ into the ice Lice was measured at its installation thickness Hice, equal to the height of the cage (tank, box), and the profile of the hole formed in the ice. At the same time in a case of penetration of the entire ice thickness, a characteristic hole profile is obtained that has an ejection funnel from the front surface (Df, Hf), a spall funnel from the rear surface (Ds, Hs) and a through-hole of a cylinder-conical shape with an average hole diameter d (Figure 2). For more accurately determine the profile of the through hole and evaluate the state of the material (ice) around it, in some experiments, blocks of pierced ice were extracted from the pipe and cut along the cross-section along the resulting hole.
Figure 2. Scheme of interaction of SC with ice barrier.

It was found that in the neighborhood of the through hole three zones are distinctly distinguished: the zone of fine-dispersed compacted snow-ice (zone "S") of diameter $d_{\text{S-ice}}$, which is adjacent directly to the hole and is easily removed, since it has almost no density (the density of the caked snow is 200 ... 400 kg / m$^3$); zone of fine-crystalline crushed ice particles (zone "I") of diameter $d_{\text{cr}}$, more solid, but unconnected with the bulk of the ice; zone of cracking (zone "T") in an array of diameters $d_T$. This feature is noted also in work [8].

In the experiments, the open-shell charges of the standard cumulative perforators PKOS-32 ($d_{\text{CH}} = 20 \text{ mm}$, $h_{\text{CH}} = 15 \text{ mm}$, $d_0 = 18 \text{ mm}$, copper conical liner, $2 \alpha = 75 ^\circ$, $d_0 = 0.6 \text{ mm}$, $m_{\text{EC}} = 3.4 \text{ g}$) and ZPKO-73 ($d_{\text{CH}} = 36.5 \text{ mm}$, $h_{\text{CH}} = 38 \text{ mm}$, $d_0 = 33 \text{ mm}$, copper conical lining, $2 \alpha = 60 ^\circ$, $d_0 = 0.9 \text{ mm}$, $m_{\text{EC}} = 28 \text{ g}$) equipped with phlegmatized hexogen ($\rho_{\text{EC}} = 1.65 \text{ g / cm}^3$, $D = 8100 \text{ m / s}$) are used, as well as a laboratory charge of SC-50 from a mixture of Composition B ($\rho_{\text{EC}} = 1.6 \text{ g / cm}^3$, $D = 7600 \text{ m / s}$) having the following geometric parameters: $d_{\text{CH}} = 50 \text{ mm}$, $d_0 = 45 \text{ mm}$, copper conical lining, $2 \alpha = 50 ^\circ$, $d_0 = 0.7 / 1.4 \text{ mm}$, $m_{\text{EC}} = 275 \text{ g}$, where $m_{\text{EC}}$ is the mass of the charge EC, $\rho_{\text{EC}}$, $D$ - density and velocity of detonation EC. The charges were detonated by means of high-speed electric detonators 9VP through a thin layer of highly sensitive elastic EC.

The results of laboratory experiments on the penetration depth of Lice are given in Table 1. In the same place, for comparison, the results of calculations based on the well-known engineering method of V.M. Marinin [5], stated in earlier work of authors [6], and also the known data from of natural experiments using SC with a diameter $d_{\text{CH}} = 70 ... 215 \text{ mm}$ with conical steel SCL for penetrating ice (frozen ground) barriers are given [3, 8].

The best relative results were obtained for an SC with a diameter $d_{\text{CH}}= 50 \text{ mm}$ (variant No. 3, Table 1), which were: $\text{Lice} = (18 ... 20) d_{\text{CH}}$, $d = (0.5 ... 0.6) d_{\text{CH}}$. In comparison with the known results of natural experiments (variants No. 4 and No. 5, Table 1), the data of laboratory experiments are maximally underestimated.

In general, SC with copper and steel conical SCL are capable of penetrating a semi-infinite barrier from solid ice (frozen ground) to a depth of at least (20 ... 25) $d_{\text{CH}}$, with an average diameter of the through-hole being at least ($0.6 ... 0.7) d_{\text{CH}}$, where $d_{\text{CH}}$ is the diameter of the charge EC. When the barrier penetrates the final thickness, this value increases by 10 ... 15% and a pronounced spall funnel appears (Figure 2). This forecast is based on experiments made in middle latitudes on fresh ice. Obviously, in conditions of real Arctic sea ice and substantially low below-zero temperatures, the penetration capacity of SC can decrease.
Table 1. The results of calculations for the penetration of ice by a SC

| Mechanical and structural parameters |
|--------------------------------------|
| Variant of calc. | Parameters of SC (Figure 1) | Calculations by engineering methods | Experiment |
| d(CH)_, mm | SCL’s shape | SCL’s material | L_ice, mm | d, mm | L_ice, mm | d, mm |
| 1 | 20 | cone 2α = 75° | copper | 218 | 8.8 | 225...250 | 8..10 |
| 2 | 36 | cone 2α = 60° | copper | 314 | 15.9 | 325 | 15 |
| 3 | 50 | cone 2α = 50° | copper | 915 | 23.2 | 925 | 30 |
| 4 | 70 | cone 2α = 50° | steel | 1310 | 32.7 | 1300 | 38...44 |
| 5 | 215 | cone 2α = 70° | steel | 2034 | 127.2 | 2000 | 160 |

As a result of the experimental researches, the sizes of the identified zones of weakened ice strength were determined during penetration of SC with copper conical liners with a cone angle of 2α = 50...75°, which were: d_s-ice = (2 ... 3)d(CH), d_c = (4 ... 5) d(CH), d_T ≥ 20d(CH) (Figure 2). The provided data indicate that in actual practice around the hole in ice from the action of SC a certain "fictitious" destruction zone with a diameter of approximately (2 ... 5)d(CH) is formed for SC with high copper conical lining. The dimensions of this zone depend on the SCJ parameters: more massive and low-gradient jets (conical liners with large solution angles 2α = 90 ... 140° and hemispherical linings) should provide larger sizes, in particular, zones "S" and "I". The same tendency should be observed when using steel and aluminum (instead of copper) as SCL material. In practical terms, this can be important for the subsequent action on a weakened ice of a high explosive EC charge or a high-speed penetrating solid cylindrical element [9, 10].

3. Numerical researches
To estimate the cumulative effect on ice barriers, SC calculations with conical and hemispherical copper SCL (Figure 1) using numerical simulation methods [5, 11, 12] were performed.

The tasks of penetrating the ice barrier with cumulative charges with conical and hemispherical facing were solved in two stages.

At the first stage, the cumulative effect of charges on a steel barrier was investigated with the aim of justifying the applicability of the chosen mathematical model for solving this class of problems.

Wherein thickness of the steel barrier was 180 mm, the focal length F = 50 mm. The free space around the SC and the obstructions is filled with air. The dimensions of the calculated area were: 250 mm (≈ 6.9 d(CH)) along the z axis, 100 mm (≈ 2.8 d(CH)) along the r axis.

In the mathematical formulation of the problem for steel, an ideal elastic-plastic model with destruction was accepted. The criterion of destruction was taken in the form \( \sigma_r > \sigma_s \), where \( \sigma_s \) is the spall strength of the material. For the liner material (copper), an ideal elastic-plastic model without destruction was accepted.

As the equations of state (EQS) of interacting media, the following ratios were used: for steel and copper – barotropic dependence; for detonation products - EQS in the form of JWL; for air - EQS of
ideal gas. Parameters in this equation were accepted: for steel: \( \rho_0 = 7.85 \text{ g/cm}^3 \), \( K = 175 \text{ GPa} \); \( G = 80.8 \text{ GPa} \); \( Y = 0.8 \text{ GPa} \); \( \sigma_p = 1.65 \text{ GPa} \); for copper: \( \rho_0 = 8.96 \text{ g/cm}^3 \), \( K = 152.8 \text{ GPa} \); \( G = 39.9 \text{ GPa} \); \( Y = 0.1 \text{ GPa} \); for air: \( k = 1.4 \); \( \rho_0 = 1.225 \times 10^{-3} \text{ g/cm}^3 \), \( p_0 = 1.013 \times 10^{-4} \text{ GPa} \).

The characteristics for EC and the constants in EQS in the form of JWL were calculated using the procedure [13] and are presented in table 2.

The boundary conditions were assigned as follows:
- on contact surfaces \( \sigma_{n1} = \sigma_{n2} \).
- the parameters at the front of the detonation wave correspond to the parameters of the Chapman-Juge.
- conditions for the flow of the medium outflow along the boundaries of the calculated area that are not in contact with the barrier material are established.

The results of the performed calculations are illustrated in figure 3.

| Parameter | Value |
|-----------|-------|
| \( \rho_0 \), g/cm\(^3\) | 1.65 |
| \( D \), km/s | 8.1 |
| \( Q \), kcal/kg | 1250 |
| \( Q \), MJ/kg | 5.23 |
| \( p_{CJ} \), GPa | 27.0 |
| \( A \), GPa | 1200 |
| \( B \), GPa | 44.1 |
| \( r_1 \) | 5.91 |
| \( r_2 \) | 1.82 |
| \( \omega \) | 0.32 |
| \( k \) | 3.0 |
| \( \varepsilon_0 \), GJ/m\(^3\) = GPa | 8.64 |

As can be seen from figure 3a, the penetration depth of the steel barrier by the charge ZPKO-73 with a conical copper liner is approximately 87 mm, which differs from the experimental results (85 mm) by only 2%, with the diameter of the formed whole being approximately 12 mm. This allows us to state that the chosen mathematical model corresponds to reality. The penetration depth of steel SC with hemispherical liner (see figure 3b) is approximately 40 mm, the jet, as in the previous case, is clogged into a hole with a diameter of 20 mm.

Thus, based on the results of numerical calculations, the penetration depth of a steel semi-infinite SC with a conical copper SCL is at least 2 times greater than the depth of penetration of SC with a hemispherical SCL, however, the diameter of the hole formed when using hemispherical SCL is about 1.7 times larger.

At the second stage, the effect of the same SC on the ice barrier was investigated. The thickness of the ice barrier was 740 mm. The dimensions of the calculated area were: 750 mm (\( \approx 20.8 \text{ d}_{CH} \)) along the z axis, 100 mm (\( \approx 2.8 \text{ d}_{CH} \)) along the r axis.
**Figure 3.** Results of calculations the penetration of the of steel barrier by SC (in different shades the density field is shown): a - with conical liner; b - with hemispherical liner.

Similar equations of state for ice in the mathematical formulation were given; the ice behavior model is an ideal elastoplastic with destruction. The corresponding characteristics of ice: \( \rho_0 = 910 \text{ kg/m}^3 \), \( K = 9.9 \text{ GPa} \), \( G = 3.6 \text{ GPa} \), \( Y = 0.01 \text{ GPa} \), \( \sigma_\rho = 0.003 \text{ GPa} \) [7].

The results of the calculations are shown in figure 4.

**Figure 4.** Results of calculations of penetration of the ice barrier for the moment of time \( t = 1400 \mu\text{s} \) (in different shades the material state field is shown): a - with conical liner, b - with hemispherical liner.

As can be seen in Figure 4a, the penetration depth of the ice SCJ formed from the conical liner is about 650 mm, and the diameter of the hole formed is approximately 18 mm. A jet of hemispherical liner provides a cavern in the ice with a depth of approximately 500 mm and a diameter of about 30 mm (figure 4b).

Thus, the depth of penetration of ice when using a charge with a conical copper SCL is approximately 1.5 times greater than when using a charge with a hemispherical liner, however, the diameter of the hole formed is 1.7 times smaller.

At the same time for both cases of SCJ penetration into the ice (see figure 4), it should be noted the following:
- along all width of an ice barrier of final thickness active crack propagation and strong destruction of the surface layer of ice are observed, followed by its outflow (the thickness of the ejected part is approximately 70 mm for both cases).
• in the finite thickness barrier, there is a splitting having parameters $D_S \approx 120$ mm, $H_S \approx 40$ mm for both cases (figure 2).
• SCJ pestle, formed from conical liner, does not get stuck in the punched hole, but continues to penetrate into the barrier, which was also observed in experimental studies (at the time of 2820 μs, pestle penetrates the ice barrier through and through), in the case of hemispherical liner such a pestle is not formed.

In comparison with the data of Table. 1 the obtained results of numerical calculations give overestimated results in relation to the laboratory experiment and calculation by the engineering method (variant No. 2). At the same time, the obtained results fit perfectly into the recommended range of penetration depths and hole diameters in the ice barrier under the action of SC with conical and hemispherical liners.

4. Conclusion
As a result of the laboratory experiments and theoretical researches, the features of the penetration of ice barriers by axisymmetric SC with conical and hemispherical SCL are studied. The obtained results can be used in the development of appropriate explosive devices for the destruction of the ice cover.

Acknowledgment
The work was financially supported by the Ministry of Education and Science of the Russian Federation within the framework of the basic part of the state task under the section "Initiative Scientific Projects" (code 9.5330.2017.BP).

References
[1] Babkin A V, Veldanov V A and Gryaznov E F 2016 Ammunition (Moscow: BMSTU Publishing) p 506
[2] Minin I V and Minin O V 2013 Shaped charges (Novosibirsk: SGGA) p 200
[3] Ladov S V and Kobylin I F 1995 Use of cumulative charges in explosive technologies (Moscow: BMSTU Publishing) p 47
[4] Walters W P and Zukas J A 1989 Fundamentals of shaped charges (N.Y.: John Wiley and Sons Publishing) p 398
[5] Andreyev S G, Babkin A V and Baum F A 2004 Physics of explosion (Moscow: Fizmatlit Publishing) p 656
[6] Ladov S V, Kolpakov V I and Fedorov S V 1995 Features of penetration the ice and grunto-concrete barriers cumulative charges Defensive technique 4 39–45
[7] Maeno N 1988 Science about ice (Moscow: Patterus Publishing) p 231
[8] Ozeretskovskiy O I 2007 Action of explosion on underwater objects (Moscow: Federal State Unitary Enterprise TsNIIHM Publishing) p 262
[9] Ladov S V, Klimachkov S I, Okhitin V N and Fedorov S V 2018 About a possibility of use of the explosive device the combined type for destruction of an ice cover Engineering Journal: Science and Innovation 2 74.
[10] Veldanov V A, Isaev A L, Ladov S V and Fedorov S V 2002 Penetration of a solid cylindrical body into the continuous and weakened by an opening ice Defensive technique 11 46–51
[11] Kolpakov V I, Ladov S V and Rubshov A A 1998 Numerical simulation of shaped charges (Moscow: BMSTU Publishing) 87–92
[12] Fedorov S V, Ladov S V and Nikolskaya Ya. M 2018 Comparative analysis of formation of shaped charge jets from conical and hemispherical liners Engineering Journal: Science and Innovation 1 73.
[13] Kolpakov V I 2016 Determination of the constants of the equation of state of detonation products in the form of Jones-Wilkins-Lee Izvestiya RARAN 4 28 87–92