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PROBLEM OF INCREASING THE SURVIVABILITY OF TWO-STAGE BALLISTIC GUNS

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The paper proposes methods for increasing the survivability of light-gas guns, including new designs and nonconventional modes of shot. It is established theoretically and experimentally that a decrease in the cone angle of the conical adapter to 2.5–3° leads to a severalfold increase in the survivability of the high-pressure chamber. A compound piston with a liquid or gel-like filler is designed. The mode of shot from a light-gas gun with superlight pistons and without a diaphragm is justified and tested experimentally. Conical and measuring adapters with liners made of thermally- and wear-resistant alloys are designed to prevent ablation of the light-gas gun barrel.

Two-stage, light-gas guns have been widely used in aeroballistic studies and in investigations of high-velocity interaction in the speed range 2.5–10.0 km/sec [1, 2]. Recently, light-gas guns have been used as preaccelerators in combined methods of acceleration to attain velocities as high as 16 km/sec [3]. An analysis of experiments with acceleration velocities higher than 8 km/sec shows that one of the main problems is the survivability of light-gas guns [4–6]. In solving problems of high-velocity acceleration, it is necessary to seek a compromise between attainment of the highest speeds of a projectile with the greatest possible weight and appropriate survivability of the gun. Studies of the survivability of the main units and details of a light-gas gun with a deformable piston show that the conical adapter and ballistic barrel of the gun frequently get out of order. The conical adapter undergoes mechanical failure (swelling) even if it is made of two or three layers fastened together [4], and the ballistic barrel is subjected to thermal erosion [6]. In the present paper, we propose methods for increasing the survivability of light-gas guns under limiting operating conditions. New designs and nonconventional operation regimes of light-gas guns are used.

An analysis of the data of [4–6] on the strength properties and survivability of the main units of light-gas guns shows that a determining factor in the survivability of the high-pressure chamber is the stress that arises in the plastic piston during its acceleration in the conical segment of the chamber. Using methods of optimal design of light-gas guns [7] and experimental studies of light-gas guns [4], it is shown that as the mass of the piston increases, the muzzle velocity of projectiles becomes higher. The mass of the piston was increased using lead inserts and compound pistons with metal and polyethylene sections [7]. In the experiments of [5], the metal section was replaced by a fluorine plastic section.

Theoretical and experimental studies of the deformation of a plastic (polyethylene) piston during shot from a light-gas gun show that maximum stresses in the piston and on the internal surface of the conical segment of the light-gas gun barrel depend appreciably on the length of the conical segment (cone angle). In this case, a decrease in the cone angle leads to a decrease in the maximum loads in the high-pressure chamber passage. In addition, from internal-ballistic calculations for light-gas guns [7] it follows that by decreasing the cone angle, it is possible to attain the same muzzle velocity at lower maximum pressures on the bottom plate of the projectile.

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TABLE 1

Shot parameter	Calculation No.								
	1	2	3	4	5	6	7	8	9
Powder	6/7	6/7	6/7	6/7	6/7	VT	VT	VT	VT
q, g	0.8	0.5	0.5	0.8	0.5	0.5	0.5	0.4	0.3
ω, g	200	200	205	205	202	170	170	170	175
p_0, MPa	1.2	1.2	1.1	1.25	1.1	0.8	0.7	0.6	0.5
$M_{\rm p}$, g	225	225	135	205	175	30	30	25	25
$p_{\rm ch,max}$, MPa	192	192	131	183	155	152	151	145	156
$p_{\rm p,max}$, MPa	3013	3124	2508	2893	2706	1080	1172	1054	1217
$p_{\rm g,max}$, MPa	1716	1708	1403	1541	1426	992	1068	940	1128
$T_{\rm g,max}$, K	2415	2396	2349	2346	2368	2693	2875	2902	3253
$p_{\rm pr,max}$, MPa	486	334	328	479	335	395	449	339	309
$U_{\rm pr}$, km/sec	7.99	7.64	8.08	8.05	8.16	8.25	8.61	8.66	9.71
$p_{\rm b}$, MPa	30	30	70	30	30	1	1	1	1
l, mm	185	185	185	370	370	370	370	370	370

Table 1 lists the main calculated shot parameters under various loading conditions for an LGG-2 light-gas gun [4] [q is the mass of the accelerated assembly, ω is the mass of the powder charge, p_0 is the initial pressure of the light gas (hydrogen), $M_{\rm p}$ is the mass of the piston, $p_{\rm ch,max}$ is the maximum pressure in the powder chamber, $p_{\rm p,max}$ is the maximum stress in the piston, $p_{\rm g,max}$ is the maximum pressure of the light gas, $T_{\rm g,max}$ is the maximum temperature of the light gas, $p_{\rm pr,max}$ is the maximum pressure on the bottom plate of the projectile, $U_{\rm pr}$ is the muzzle velocity of the projectile, $p_{\rm b}$ is the boosting pressure, and l is the length of the cone].

Calculation Nos. 1–3 correspond to the experimental data obtained on a light-gas gun with a conical segment 185 mm long, and calculation Nos. 4–9 refer to a hypothetical high-pressure chamber with a length of the conical segment of 370 mm, which is twice that in the first case. A comparison of the calculation results for calculation Nos. 1, 2, 4, and 5 shows that with the longer adapter, the same velocities can be attained for much smaller (by 30%) maximum pressures of the light gas, stresses in the piston, and maximum pressures on the projectile bottom plate. This is typical of "light" projectiles with a relative mass of $C_q \leqslant 1$ g/cm^3 ($C_q = q/d^3$, where d is the bore). This was taken into account in the design of a unified complex (T-110) of PKh experimental ballistic guns [8]. Thus, a PPKh23/8 light-gas gun incorporated in this complex has a piston bore $D = 23$ mm, an 8-mm ballistic bore, a high-pressure chamber with a conical segment 300 mm long, and a cone angle of 2.85°. In the light-gas gun described in [4–6], the cone angle is 8° or larger. The manufacture of a high-pressure chamber with a longer conical segment for a small-bore, light-gas gun involves considerable technological difficulties, Therefore, in a PPKh34/23/8 light-gas gun with an 8-mm ballistic bore and a 34-mm piston bore, which is incorporated in the T-110 complex, the high-pressure chamber comprises two conical adapters and a cylindrical insert of 23 mm diameter (Fig. 1).

Another method for decreasing the stress in a piston in its motion in a conical adapter is by changing the design and material of the piston. Indeed, the losses due to the deformation and friction of the piston, besides decreasing the survivability, lead to a decrease in the acceleration velocity in the light-gas gun. It is known that at strain rates typical of light-gas guns with a light piston, the dynamic yield strength of polyethylene increases markedly. As a result, the initial shape of the piston remains unchanged at pressures many times higher than the yield strength of polyethylene (15–20 MPa) [9, 10].

The piston design we propose is given in Fig. 2. It consists of two obturators made of polyethylene and a liquid or gel-like filler occupying the space between them. The filler can be a volatilizing liquid (ether or alcohol) or a thermally stable lubricant, for example, gun lard. The losses due to deformation and friction

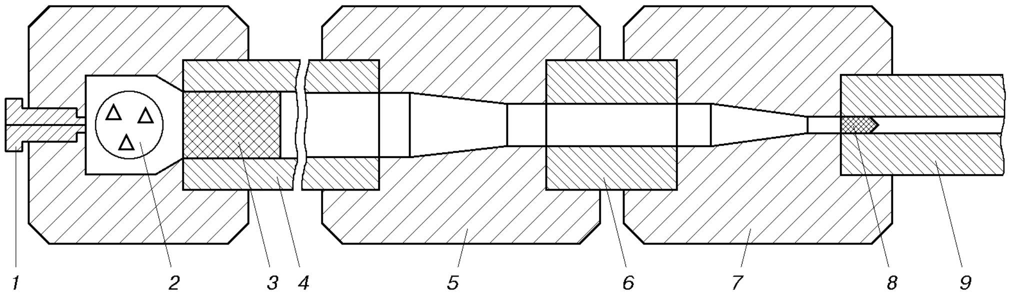

Fig. 1. Diagram of a light-gas gun with a compound conical adapter: 1) ignition fuse; 2) powder chamber; 3) piston; 4) compression chamber; 5) first section of the conical adapter; 6) cylindrical insert; 7) second section of the conical adapter; 8) projectile; 9) barrel.

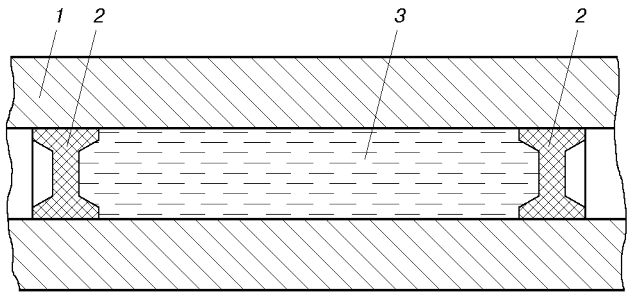

Fig. 2. Diagram of a compound piston: 1) compression chamber; 2) obturators; 3) fluid filler.

of this piston are much smaller than those for a monolithic piston from polyethylene, and this increases the survivability of the light-gas gun and the acceleration velocity.

These results were taken into account in designing a PPKh23/8 light-gas gun in which the survivability of the high-pressure chamber is more than 100 shots in operation regimes with an acceleration velocity higher than 8 km/sec. In such regimes, the survivability of the barrel is, on the average, 20 shots. After that, the barrel is reclaimed by repeated honing, which increases the bore by 0.1–0.2 mm.

An analysis of data obtained from tests of an LGG-2 light-gas gun [4] and a PPKh23/8 light-gas gun shows that when a relatively heavy piston is used, the muzzle velocity of a projectile increases insignificantly with decrease in its mass, and, in some cases, even decreases. This is explained by the fact that a "light" projectile "escapes" from the piston, and the hydroeffect [1] on the muzzle velocity of the projectile becomes weak or is absent. The use of relatively heavy pistons implies the obligatory use of a diaphragm with a breaking pressure of about 60–70 MPa. A PPKh23/8 light-gas gun uses a diaphragm made of 12Kh18N10T stainless steel 2 mm thick, which breaks at a pressure of about 200 MPa. At the moment of breaking, the projectile is subjected to peak loads, which sometimes lead to fracture of the bottom plate. In addition, when the maximum temperature of the light gas increases and ablation traces appear on the surface of the ballistic bore, precisely the surface of the diaphragm is subjected to maximum ablation of the metal. Thus, an increase in the mass of the piston leads to a decrease in the survivability of the high-pressure chamber.

In the present work, we attempted to determine acceleration modes for "light" projectiles ($C_q \leqslant 1$ g/cm^3). An analysis of the results of a large series of calculations shows that, in this case, modes of shot with light pistons and without a diaphragm are most reasonable. As compared to conventional acceleration modes [1, 4–6], the main features of the proposed modes are as follows:

— the powder charge is increased by 10–20%, a finer fast-burning powder is used (for an LGG-2 light-gas gun, 6/7 powder is replaced by 4/7 powder or VT powder);

— the mass of the piston decreases by a factor of 2 or 3, and its relative mass is $C_{q,\mathrm{p}} = M_\mathrm{p}/D^3 \approx 1.5$–$2.5$ g/cm^3, whereas in experiments on a PPKh23/8 light-gas gun, we used pistons with $C_{q,\mathrm{p}} \approx 4.5$–$5.5$ g/cm^3 (the pistons used in the LGG-2 had a relative mass of $C_{q,\mathrm{p}} \approx 5$–$8$ g/cm^3);

— the initial pressure of the light gas is decreased by a factor of 1.5–2.5 (from 1.2–1.8 to 0.3–0.8 MPa).

TABLE 2

ω, g	M_p, g	$p_{ch,max}$, MPa	$p_{p,max}$, MPa	$T_{g,max}$, K	$p_{pr,max}$, MPa	U_{pr}, km/sec
55	25	151	727	3633	275	8.29
60	23	186	864	4040	331	8.84
60	25	191	940	4218	355	9.05
60	28	199	1041	4442	389	9.32
65	23	236	1081	4617	419	9.58

Tests showed that, using a bottom plate of a rather rigid material (Phenylon, Graphilon, or polycarbonate), it is possible to attain a projectile boosting pressure higher than the initial light-gas pressure in the compression chamber and to ensure hermetization of the compression chamber when it is filled with the light gas. This simplifies the design of the boosting unit (see Fig. 1).

Calculations of shot parameters for the LGG-2 with a light piston and without a diaphragm are given in Table 1 (calculation Nos. 6–9). The absence of a diaphragm was modeled by specifying a boosting pressure of $p_b = 1$ MPa. The calculations show that with variation in the static friction force over a broad range, the shot parameters practically do not vary. Thus, variation of p_b from 1 to 10 MPa changed significantly only the maximum pressure on the projectile bottom plate (by 5%). From the calculation results it follows that, in this case, a muzzle velocity of about 8 km/sec for a projectile with a mass of 0.5 g can be obtained at maximum pressures of the light gas lower than 1000 MPa, while for heavy pistons and diaphragms, the maximum pressures are 1700–2000 MPa. Accordingly, the maximum stresses in the piston decrease during its deceleration in the cone. For projectiles with masses of 0.3 and 0.4 g, the muzzle velocity can be increased to 9 km/sec or more.

Table 2 gives calculations of shot parameters for a PPKh23/8 light-gas gun with a light piston and without a diaphragm. The calculations were performed for VT powder and a projectile with a mass of $q = 0.3$ g and an initial light-gas pressure of $p_0 = 0.7$ MPa. The calculation results show that in these shooting modes for this light-gas gun, it is also possible to reach velocities of about 9 km/sec for a projectile with a mass of 0.3–0.5 g with reasonable survivability of the main units of the light-gas gun. At the initial stage of investigation, we used the calculation program of [11] and then the calculation program of [7], in which the powder combustion law was modified according to [9] and the law of motion of the piston was taken from [10].

The mode of shot without a diaphragm, as proposed above, was tested experimentally on a PPKh23/8 light-gas gun. The results of the tests are given in Table 3 (l_b is the length of the ballistic barrel), and they confirm the serviceability of the light-gas gun in this mode of shot and the possibility of attaining velocities of about 7 km/sec in a trouble-free operation regime. The decrease in the velocity in experiment No. 80 is explained by break of the light gas through the joint. In this connection, the joint was modified by replacing the flat sealing ring from 12Kh18N10T stainless steel with an elastic sealing ring from beryllium bronze (Fig. 3). The obturator ring is manufactured so that its height is 0.3 mm larger than the height of the shoulder on the barrel against which the ring is butted up. In this case, after the barrel is joined to the conical adapter, the ring is in a compressed state and keeps track of the displacement of the barrel relative to the conical adapter during shot, thus ensuring obturation of the boosting unit. In addition, on the internal surface of the ring there is a conical groove. Reaching the groove, the expanding light gas spreads the ring and ensures additional self-obturation by the principle of lenticular sealing. Subsequent experiments confirmed the reliability of obturation of this joint, and, moreover, one ring can be used several times.

In the tests, computed acceleration velocities (8–9 km/sec) were not attained, and this required further studies to determine the main regularities of the shot process and to validate the physicomathematical models used in the calculations [9, 10].

TABLE 3

Experiment number	q, g	ω, g	M_p, g	p_0, MPa	l_b, m	U_{pr}, km/sec
78	0.40	50	20	0.9	2.11	6.32
79	0.39	53	20	0.9	2.11	6.50
80	0.41	58	20	0.9	2.11	5.68
81	0.35	58	20	0.9	2.11	6.88
82	0.35	63	20	0.11	2.11	6.75
83	0.29	63	20	0.11	2.11	6.93
84	0.29	63	19	0.11	2.11	6.98
85	0.32	66	23	0.12	2.11	6.91
86	0.29	66	18.5	0.11	2.47	7.18

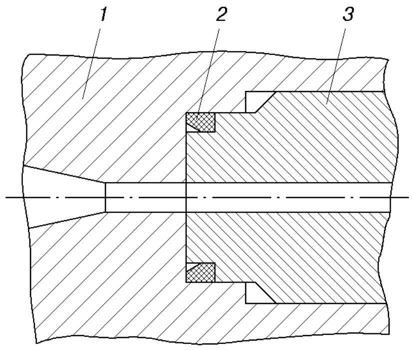

Fig. 3. Diagram of the joint: 1) conical adapter; 2) elastic obturator ring; 3) barrel.

In the experiments described above, the decrease in the acceleration velocity may be caused, in particular, by ablation of the internal surface of the conical adapter channel and the barrel, as a result of which the light gas becomes laden with metal particles. The calculations of [6, 12] show that in light-gas guns, the internal surface temperature of the conical adapter can exceed the melting point of steel.

Various methods have been proposed to apply thermal- and wear-resistant coatings to the thermally stressed segments of the light-gas gun barrel, in particular, the gas-phase deposition of tungsten [13] and chromium plating. At present, however, there are no elaborate technologies for applying protective coatings to the thermally stressed segments of the light-gas gun barrel, in particular for light-gas guns of small diameter. At the same time, the calculations of [6, 12] show that only the internal surface of the conical adapter liner and the initial section of the barrel (segment with a length of 20–30 diameters) are subjected to intense heating and melting. It is suggested, therefore, that the conical adapter liners for light-gas guns of small diameter be made of alloys whose properties ensure the required strength of the conical adapter and prevent melting of the liner internal surface.

In the model gun of [9], the pressure and time of diaphragm rupture were determined using a measuring adapter, which was placed between the conical adapter and the measuring fuse. Later, these adapters were also used during shot. It was established experimentally that, in this case, the decrease in the acceleration velocity is about 1%. If this adapter has a liner made of a thermally stable alloy, for example W–Ni–Fe alloy, this prevents ablation of the barrel or decreases it to a great extent. The strength properties of some alloys compares with those of the best gun steels. Moreover, the thermal conductivity of W–Ni–Fe alloy is severalfold higher than that of steel. This facilitates rapid supply of heat into the liner body and a decrease in the liner surface temperature. The boosting unit design for such a light-gas gun is given in Fig. 4.

It should be noted that ablation of the conical adapter channel and the barrel does not always lead to a decrease in the projectile velocity since ablation begins after the projectile has gained a considerable velocity. The effect of loading of the light-gas stream with metal particles on the projectile velocity was

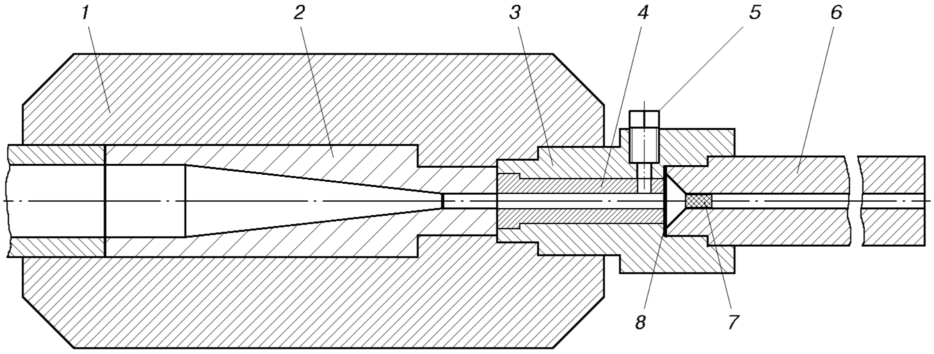

Fig. 4. Diagram of the boosting unit: 1) conical adapter; 2) conical adapter liner (W–Ni–Fe); 3) measuring adapter; 4) measuring adapter liner (W–Ni–Fe); 5) T10000 pressure gauge; 6) barrel; 7) projectile; 8) diaphragm.

examined using the following procedure. Once the melting point of steel is reached, a characteristic is issued downstream from a relevant point in the calculation domain of the light-gas. If the characteristic catches up with the projectile when the latter moves in the barrel, the loading of the stream with metal particles affects the muzzle velocity of the projectile. Otherwise, ablation of the barrel does not influence the muzzle velocity. The calculations show that for "light" projectiles, the second case is typical.

It is possible that there is another mechanism of erosion of the barrel bore. Thus, according to [14], bore erosion can be caused by a considerable decrease in the strength of steel at temperatures well below the melting point. In this case, bore erosion begins much earlier, and loading of the light gas with metal leads to a decrease in the muzzle velocity of the projectile.

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