Research, design, and fabrication of a gas-generating propellant charge for a three-chamber underwater vehicle simulator launch system

Nguyen Duc Long, Nguyen Van Hung, Pham Van Thuan*, Hoang Van Hung

Institute of Propellants, Explosives, 192 Duc Giang, Viet Hung, Hanoi, Vietnam.
*Corresponding author: phamthuan9011@gmail.com

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ABSTRACT

This paper presents selected results on the research, design, and fabrication of a gas-generating propellant charge using domestic technology, based on an internal ballistic model of a three-chamber launcher. Following the study and calculation of the igniter mass, propellant grains and the gas-generating charge were manufactured, with an igniter mass of 32,8-33,2 g and a total propellant mass ranging from 3580 g to 3590 g. Ground firing tests on a test stand met the required performance criteria. The charge was subsequently subjected to firing tests to evaluate its capability to propel an underwater vehicle simulator with a mass of 2200-2300 kg within a launch tube system. The results show that the pressure–time profiles of the propellant gases in the charge chamber (chamber 1), the accumulator (chamber 2), and the launch tube (chamber 3) are in complete agreement with theoretical predictions. The obtained internal ballistic performance parameters include the maximum propellant gas pressures in the charge chamber, the accumulator, and the launch tube, which are 180,21 bar, 92,56 bar, and 11,04 bar, respectively. The operating time of the propellant charge is 390 ms, and the exit velocity of the vehicle simulator from the launch tube reaches 21,95 m/s, satisfying the technical requirement.

Keywords: Propellant; Gas-generating propellant charges; Underwater vehicle; Launch system.

1. INTRODUCTION

Currently, in many countries worldwide, large underwater vehicles (with controls), with masses ranging from 1500 kg to 2300 kg, are deployed on various types of surface vessels and submarines. These systems are capable of maritime surveillance and area protection, as well as seabed exploration and reconnaissance. They are regarded as one of the modern and widely adopted categories of equipment, featuring numerous advanced capabilities and being extensively utilized across the maritime domains of many nations [1-4].

Controllable underwater vehicles are launched from launch tubes integrated into launcher systems installed on vessels operating within the maritime areas of our country. For hot-launch operations, a gas-generating propellant charge is used, where the combustion of the propellant produces high-pressure gases that propel the controllable underwater vehicle out of the launch tube at the required velocity (15–25 m/s) [1, 3, 4].

Therefore, the research and development of new gas-generating propellant charges that meet technical specifications using domestic technologies constitute a highly innovative and urgent task.

This paper presents some key results from the research, design, fabrication, and testing of gas-generating propellant charges for a three-chamber launcher of a controllable underwater vehicle simulator.

2. RESEARCH OBJECTIVE AND METHODOLOGY

2.1. Research object

The object of this research paper is the gas-generating propellant charge for a three-chamber launcher of a controllable underwater vehicle simulator, developed using domestic technology and materials.

2.2. Equipment, materials and chemicals

- The gas-generating propellant charge consists of:

+ The propellant grain was researched, designed, and manufactured by Institute T in collaboration with Factory Z_1.

+ The propellant charge casing and end cap were researched and designed by Institute T and Institute C, and were manufactured in coordination with Factory Z_2.

+ The ignition system and black powder type No. 2 (fine-grained) were researched, designed, and manufactured by Institute T in collaboration with Factory Z_3.

+ The igniter charge was researched, designed, and manufactured by Institute T.

- Vehicle simulator possesses a shape, dimensions, and mass equivalent to those of a controllable underwater vehicle: Overall dimensions (diameter × length), mm: 534,4 × 7828; Mass, kg: from 2200 to 2300.

2.3. Methods

- The study integrates theoretical and experimental investigations, including computational analysis, algorithm development, prototype fabrication, and measurement of the product's technical characteristics.

- The operating principle of a three-chamber launch system for an underwater vehicle simulator is described in [3] (Figure 1).

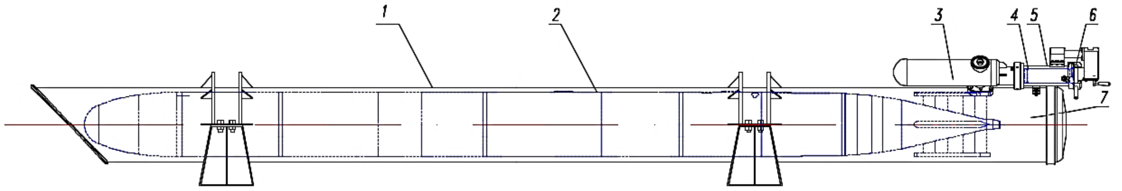


Figure 1. *Three-chamber launch system for an underwater vehicle simulator: 1 - Launch tube (chamber 3); 2 - Underwater vehicle simulator; 3 - The accumulator (chamber 2); 4 - The gas-generating propellant charge; 5 - The charge chamber (chamber 1); 6 - Ignition mechanism; 7 - the launch tube (chamber 3).*

- Measurement methods:

+ The pressure-time curve $P(t)$ combustion duration, and total pressure impulse were measured using the multi-channel data acquisition system DEWESoft R2DB, operating at a sampling rate of up to 1 MS/s, with an 8-bit resolution, an accuracy of $\geq$ 0,2% FSO and its synchronized accessories (pressure sensors Piezo HBM 1000 bar, 500 bar, 200 bar and measurement cables).

+ The exit velocity of the test vehicle simulator was measured using the FastCAM SA5 high-speed camera system, capable of recording up to 1.000.000 frames per second (fps) at reduced resolution and 7.500 fps at full resolution (1K × 1K, 1024 × 1024 pixels) at Institute T.

+ An experimental procedure was implemented to evaluate the operational performance of the propellant charge within the test launch tube system under loading conditions with a test vehicle simulator.

- Investigation and calculation of the ignition charge mass: Based on the formula for determining the maximum pressure under isochoric conditions according to the Nobel-Abel equation [3, 5]:

$$p_m = \frac{f_m \cdot \Delta_m}{1 - \alpha_m \cdot \Delta_m} \tag{1}$$

In there: p_m - maximum pressure (kG/dm^2); f_m, α_m, Δ_m: Propellant force, covolume of combustion products and packing density; In the case of black powder: f_m= 2,8. 10^5 (kG.dm/kg); α_m = 0,5 (dm^3/kg).

Packing density Δ_m (kg/dm^3):

$$\Delta_m = \frac{\omega_m}{V_{td0}} \tag{2}$$

Here: ω_m - Sample mass (kg); V_{td0}: The initial free volume of the combustion chamber (dm^3).

From equations (1) and (2), the expression for calculating the sample mass is obtained ω_m:

$$\omega_m = \frac{V_{td0} \cdot p_m}{f_m + \alpha_m \cdot p_m} \tag{3}$$

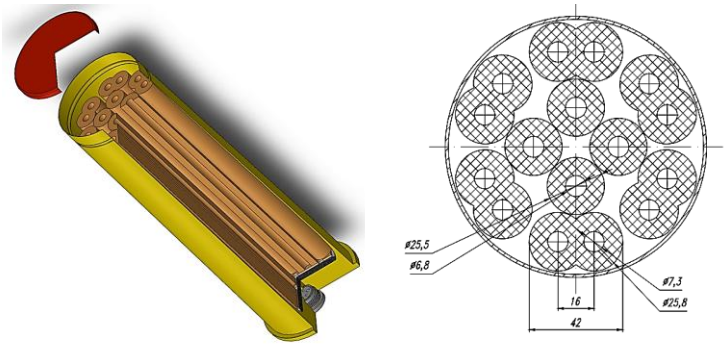
3. RESULTS AND DISCUSSION

3.1. Calculation and formulation of a single-component propellant composition for gas-generating charges

Based on studies of propellants used for gas-generating charges [3, 5], 11], the authors employed a modified RSI-grade ballistite propellant with an enhanced burning rate, achieved by replacing the mixed combustion catalyst system of lead oxide and lead salicylate with a single lead(II) oxide catalyst system, to calculate and fabricate the gas-generating propellant charge for a three-chamber working launch system of a simulated vehicle. The chemical composition (% mass.): Nitrocellulose (56,0%), Nitroglycerin (28,0%), Dinitrotoluene (9,0%), Centralit No.2 (3,0%), Vaseline (1,0%), Lead oxide (1,0%), Lead salicylate (0,5%), Calcium carbonate (1,0%), Moisture content (0,5%); The experimentally measured heat of combustion (Q_{exp}): 855,8 Kcal/kg.

3.2. The calculation and design of the propellant charge

Based on the internal ballistic model of a three-chamber launcher [3], the authors conducted research and optimization of the propellant charge design by adopting a configuration consisting of four cylindrical propellant grains and six figure-eight-shaped propellant grains, with geometries and dimensions as shown in Figure 2.



a) *b)*

Figure 2. *Configuration of the gas-generating propellant charge:*
a) Photograph of the propellant charge; b) Arrangement of the propellant grains within the propellant charge.

Based on the geometry and dimensions of the propellant grains in the gas-generating charge shown in Figure 2, and considering the actual operating principle of the launcher-vehicle simulator-propellant charge system illustrated in Figure 1, the author incorporated the pressure diaphragm rupture conditions in chambers 2 and 3 into the internal ballistic model of the three-chamber launcher [3, 4]. Subsequently, internal ballistic calculations were performed for the launcher-vehicle simulator-propellant charge system with three working chambers. The results of the internal ballistic analysis are presented in Figure 3.

From the pressure-time histories of the propellant gases in chamber 1, chamber 2, and chamber 3 (Figure 2), it can be observed that the gas pressure in chamber 1 increases rapidly from the ignition pressure p_m = 40,0 bar to a maximum value of p_{1max} = 110,10 bar at t = 0,015 s. Simultaneously, gas exchange occurs between chamber 1 and chamber 2 through the nozzle. As a result, the pressure in chamber 2 rises rapidly and reaches p_{2max} = 70,05 bar at t = 0,025 s, at which point the pressure diaphragm in chamber 2 ruptures. This rupture initiates the gas flow interaction between chamber 2 and chamber 3. The pressure in chamber 3 then gradually increases and reaches p_3 = 6,65 bar at t = 0,073 s, corresponding to the ejection pressure, at which moment the vehicle simulator begins to move. As the vehicle simulator travels along the launcher, the volume behind it increases, leading to a corresponding increase in the free volume of chamber 3. However, since the translational velocity of the vehicle simulator within the launcher is considerably lower than the gas exchange rate between chamber 2 and chamber 3, the pressure in chamber 3 continues to rise and reaches a maximum value of p_{3max} = 11,98 bar at t = 0,168 s. The combustion process continues until t = 0,394 s, when the vehicle simulator exits the launch tube.

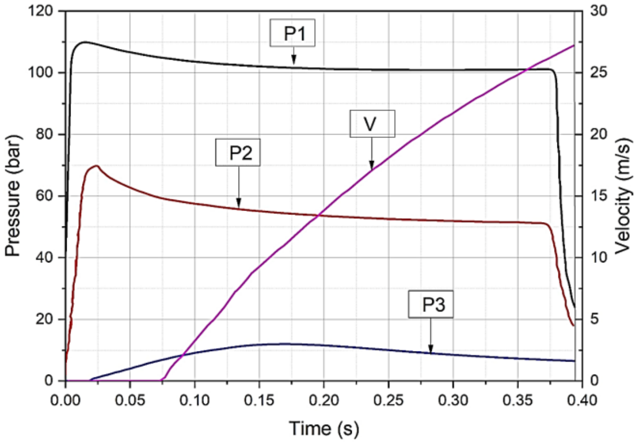


Figure 3. *The calculated results of the internal ballistic analysis include the pressure-time profiles of the propellant gases in chamber 1, chamber 2, and chamber 3, as well as the velocity-time profile of the underwater vehicle simulator.*

Based on the velocity–time curve of the vehicle simulator within the launcher (Figure 3), it can be observed that during the initial stage, the vehicle simulator remains stationary because the propellant gas pressure in chamber 3 has not yet reached the ejection pressure. At t = 0,073s, the vehicle simulator begins to move. Its velocity then increases continuously, reaching v = 27,20 m/s at t = 0,394 s, which corresponds to the end of its travel within the launch tube. Compared with the required velocity range of 15-25 m/s [3, 4], the theoretically calculated velocity exceeds the upper limit by approximately 2,2 m/s. This discrepancy arises because the theoretical model does not incorporate the aerodynamic drag coefficient acting on the vehicle simulator during its exit from the launch tube.

3.3. Manufacturing and experimental results of the propellant charge

3.3.1. Investigation and calculation of the ignition charge mass

Based on studies [3, 5] concerning ignition compositions used in propellant charges and RSI-type propellants, the authors selected No. 2 granulated black powder as the igniter for the gas-generating propellant grains. The calculation of the black powder mass, ensuring reliable ignition of the main propellant charge while maintaining the maximum gas pressure (p_{max}) within the prescribed limits, plays a critical role in the combustion process and the overall operation of the propellant charge. This is essential for guaranteeing the structural integrity of the charge casing and the launch system components (charge chamber, accumulator, launch tube, etc.). By combining theoretical calculations with experimental firing tests conducted on a test stand, the authors determined an appropriate black powder mass that ensures proper operational behavior of the propellant charge and satisfies the specified technical requirements.

According to [5], experimental results indicate that, in order to ensure reliable ignition of the propellant within the combustion chamber, the ignition pressure must be equal to: $p_m = (30\div40).10^5$ Pa = (3059÷4079) kG/dm^2.

- The ignition pressure p_m for the gas-generating propellant charge is selected within the range of: (3059÷4079) kG/dm^2.

- By applying equation (3), the ignition charge mass for the gas-generating propellant charge was calculated as presented in Table 1.

Table 1. *Calculated ignition charge mass for the gas-generating propellant charge.*

No.	Selected ignition pressure, p_m (kG/dm^2)	Free volume of the combustion chamber W_0 (dm^3)	Calculated mass of black powder (kg)
1	3059	3,05	0,0331
2	4079		0,0441

Thus, based on the calculated results presented in Table 1, the ignition charge (black powder type No. 2, fine-grained) mass can be selected within the range of 33,0-44,0 g to ensure reliable ignition of the gas-generating propellant charge.

3.3.2. Manufacturing and test results of the propellant charge on the test stand

Based on the calculated and designed propellant charge configuration, the research team proceeded to manufacture propellant grains with dimensions meeting the specifications shown in Figure 1. The fabricated propellant charge, consisting of four cylindrical grains and six figure-eight-shaped grains, had an actual propellant mass ranging from 3580 g to 3590 g, serving for assembly and experimental testing. The ignition charge (black powder type No. 2, fine-grained) mass used was selected within the range of 33,0 - 44,0 g. The experimental firing results of the gas-generating propellant charge at temperatures of -2 °C, +20 °C, and +50 °C in the propellant chamber (chamber 1) on the test stand, with ignition charge masses ranging from 33,0 g to 44,0 g, yielded the interior ballistic performance parameters presented in Table 2.

Table 2. *Results of experimental firing tests of the gas-generating propellant charge at different temperatures in the charge chamber (Chamber 1) on the test stand, with ignition charge (black powder type No. 2, fine-grained) masses ranging from 33,0 g to 44,0 g.*

No.	Ignition charge mass, g	Conditioning temperature, ºC	Experimental results				
			p_{max}, *bar*	p_{tb}, *bar*	*t, s*	*Total pressure impulse, bar.s*	p_{max}/p_{tb}
1	44,0	+50 ºC	225,8	126,2	0,365	43,67	1,79
2	44,0	+20 ºC	196,8	104,5	0,410	42,16	1,88
3	44,0	-2 ºC	159,5	95,6	0,453	41,36	1,67
4	35,0	-2 ºC	142,6	94,5	0,448	41,11	1,51
5	35,0	+20 ºC	162,7	103,8	0,420	41,59	1,57
6	33,0	-2 ºC	129,6	96,2	0,450	40,44	1,35
7	33,0	+20 ºC	154,4	104,6	0,424	41,05	1,48
8	33,0	+50 ºC	181,8	125,8	0,367	41,14	1,45

The results presented in table 2 indicate that, with an ignition charge mass of 44,0 g, the relative deviation between the maximum propellant gas pressure p_{max} and the average pressure p_{tb} is considerable, particularly at +20 °C (p_{max}/p_{tb}=1,88) and +50 °C (p_{max}/p_{tb} =1,79). According to [5], this indicates that the ignition charge mass is excessive relative to the requirement, resulting in a relatively high maximum propellant gas pressure p_{max}, which may adversely affect the structural integrity of the propellant charge casing and the charge chamber (chamber 1). When the ignition charge mass is reduced from 44,0 g to 35,0 g, the ratio p_{max}/p_{tb} decreases significantly, reaching 1,57 at +20 °C and 1,51 at -2 °C. In particular, when the ignition charge mass is 33,0 g, the pressure ratio p_{max}/p_{tb} at different temperatures ranges from 1,35 to 1,48 (Figure 4). The corresponding pressure-time curves are fully consistent with the requirements of the ignition charge design and the internal ballistic model [5]. Therefore, the authors selected an ignition charge (black powder type No. 2, fine-grained) mass of 32,8 - 33,2 g for assembly, testing, and acceptance evaluation of the gas-generating propellant charge.

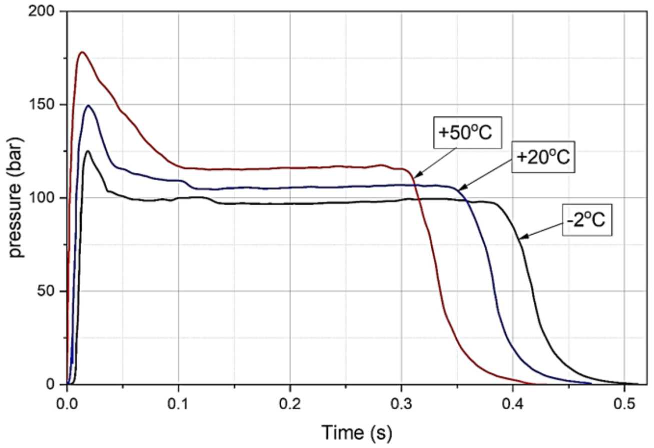


Figure 4. *Propellant gas pressure–time curves obtained from experimental firing tests of the gas-generating propellant charge in the charge chamber (chamber 1) on the test stand at -2 °C, +20 °C, and +50 °C (ignition charge mass: from 32,8 to 33,2 g).*

3.3.3. Testing the performance of the propellant charge on a test launch tube system while loading the underwater vehicle simulator

After the firing tests on the test stand met the specified technical requirements, the authors employed the gas-generating propellant charge to experimentally evaluate its capability to launch a test underwater vehicle simulator with a mass of 2200 - 2300 kg at 20 °C from the launch tube. The experimental results are presented in Table 3 and Figure 5.

Table 3. *Results of the experimental evaluation of the gas-generating propellant charge on the test launch tube system with a controllable underwater vehicle simulator (experimental) in comparison with internal ballistic calculations (theoretical).*

Maximum propellant gas pressure in the charge chamber (chamber 1) p_{1max}, bar	**Maximum propellant gas pressure in the accumulator (chamber 2) p_{2max}, bar**	**Maximum propellant gas pressure in the launch tube (chamber 3) p_{3max}, bar**	**Operating time of the propellant charge, ms**	**Exit velocity of the vehicle simulator from the launch tube, m/s**	**Note**
≤ 441,50	≤ 166,79	≤ 16,14	150 - 480	15 - 25	Technical requirements [1, 3]
180,21	92,56	11,04	390	21,95	Reality
110,10	70,05	11,98	394	27,20	Calculate

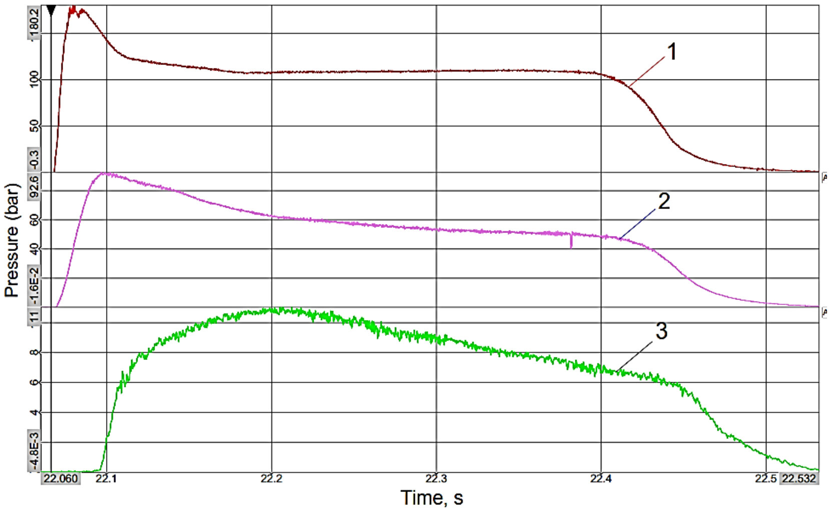


Figure 5. *Pressure–time curves of the propellant gases in the charge chamber (**1**), the accumulator (**2**), and the launch tube (**3**) for the gas-generating propellant charge on the test launch tube system with the underwater vehicle simulator loaded.*

From Table 3 and Figure 5, it can be observed that the calculated results of the internal ballistic problem, represented by the pressure–time curves for chamber 1, chamber 2, and chamber 3 (Figure 3), are in good agreement with the experimentally obtained pressure-time histories of the gas-generating propellant charge. The principal internal ballistic parameters, including the maximum pressure and operating time, show close correspondence between the theoretical predictions and the experimental measurements. The theoretically predicted vehicle simulator exit velocity (27,20 m/s) is approximately 24,0% higher than the experimental value (21,95 m/s). This discrepancy can be partially attributed to the absence of an aerodynamic drag coefficient in the theoretical model during the exit process of the vehicle simulator, as well as to uncertainties in the estimated loss and friction coefficients, which have not yet been fully calibrated to actual operating conditions. According to the results presented in Table 3, the technical performance parameters of the gas-generating propellant charge, as researched, calculated, designed, and manufactured by the authors, fully satisfy the specified requirements.

4. CONCLUSIONS

Based on the calculation and design of the propellant charge and the development of an internal ballistic model for the underwater vehicle simulator-launcher system with three working chambers-incorporating the rupture conditions of the pressure diaphragms in chamber 2 and chamber 3 as well as thermal loss coefficients, the authors determined the ignition charge mass, manufactured the propellant charge, and conducted firing tests of the gas-generating propellant charge on a test stand. Following the test firings, an appropriate ignition charge mass was selected, and the internal ballistic performance parameters were verified to satisfy the specified technical requirements. Subsequently, experimental tests were carried out to evaluate the capability of the system to launch a test vehicle simulator with a mass of 2200 - 2300 kg at 20 °C from the launch tube. The theoretical internal ballistic analysis provided predicted values for the maximum propellant gas pressures in the charge chamber (chamber 1), accumulator (chamber 2), and launch tube (chamber 3), as well as the operating time of the propellant charge and the vehicle simulator exit velocity. These values are in good agreement with the experimentally measured data obtained during the actual operation of the propellant charge. The technical performance parameters of the gas-generating propellant charge, as researched, designed, and manufactured by the authors, meet the specified requirements.

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TÓM TẮT

Nghiên cứu, thiết kế, chế tạo liều phóng tạo khí của giàn phóng vật thể mô phỏng phương tiện dưới nước có ba buồng làm việc

Bài báo trình bày một số kết quả nghiên cứu, thiết kế, chế tạo liều phóng tạo khí bằng công nghệ trong nước trên cơ sở mô hình thuật phóng trong của giàn phóng có ba buồng đốt. Sau khi nghiên cứu, tính toán khối lượng thuốc mồi, chế tạo các thỏi thuốc phóng, liều phóng tạo khí với khối lượng thuốc mồi 32,8 - 33,2 gam và tổng khối lượng thuốc phóng từ 3580 gam đến 3590 gam thử nghiệm đốt trên giá thử đạt yêu cầu, đã được đưa vào đốt thử nghiệm kiểm tra khả năng đẩy vật thể mô phỏng phương tiện dưới nước với khối lượng 2200 - 2300 kg trên hệ thống ống phóng. Kết quả thu được đồ thị quy luật áp suất khí thuốc trong bầu liều (buồng 1), trong bình tích áp (buồng 2), trong ống phóng (buồng 3) theo lý thuyết hoàn toàn phù hợp với thực tế. Các giá trị chỉ tiêu thuật phóng gồm: áp suất khí thuốc lớn nhất trong bầu liều, trong bình tích áp, trong ống phóng lần lượt là: 180,21 bar; 92,56 bar; 11,04 bar; thời gian làm việc của liều phóng 390 ms và vận tốc của vật thể mô phỏng thoát ra khỏi ống phóng 21,95 m/s đạt yêu cầu kỹ thuật.

Từ khoá: Thuốc phóng; Liều phóng tạo khí; Phương tiện dưới nước; Giàn phóng.