

Experimental Determination of the Focal Distance of Cumulative Pyrotechnic Device in Launch Vehicle Separation System

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Abstract: Pyrotechnic devices are widely used in modern aerospace engineering. One of the most effective types of pyrotechnic devices for performing obstacle separation operations in aerospace engineering is linear shaped charges. The penetration efficiency of the cumulative jet into a metal plate varies depending on the distance to the obstacle, i.e., on the focal distance. The focal distance is a key design parameter, therefore its study is extremely important for the development of effective systems. The article presents a methodology for conducting experimental research and the results of experimental research to determine the optimal focal distance for setting a linear shaped charge with a semicylindrical shaped liner with a diameter of 5 mm on an obstacle made of aluminum alloy 2219. The method for determining the optimal focal distance, the obtained data of the optimal and recommended focal distance are described. The research results provide valuable data for optimizing the mass characteristics of the structure by applying the optimal focal distance parameter for setting the linear shaped charge. This will help in the development of more efficient and reliable separation systems in aerospace engineering. The materials of the article will be useful for scientific and technical workers working on separation processes.

Keywords: aerospace engineering; experimental research; focal distance; linear shaped charge; material strength; separation system

1 INTRODUCTION

Pyrotechnic Devices (PDs) are widely used in modern aerospace engineering. They are employed for separating launch vehicle stages, detaching spent structural elements, terminating flight by shutting down the engine, and destroying the structure in case of emergency situations [1-6].

Efforts to reduce launch vehicle (LV) mass are becoming particularly important for ensuring competitiveness in the face of ever-increasing competition in the space industry. Therefore, research aimed at developing more effective solutions plays a crucial role in this direction.

Linear shaped charges (LSCs) are one of the most effective types of PDs for performing separation operations in aerospace engineering [7]. They are characterized by high energy density, small size and weight, and simple manufacturing [3, 8]. LSCs provide efficient separation of rocket structural elements by cutting the obstacle with a cumulative jet (CJ). Currently, LSCs are used in the separation systems (SS) of the following launch vehicles: Ariane-5 (France), PSLV (India), Atlas-5/551 (USA), Minuteman III (USA), Delta IV (USA) [2-5]. As a result of their operation, the separating bodies are given relative linear and angular velocities. Therefore, in some cases, LSC-based PDs can be used directly for separating passive structural elements [3], without the use of springs, pyromechanical pushers, or impulse solid-propellant engines. This feature allows for further reduction of the mass of the launch vehicle separation system.

LSCs are elongated explosive charges (ECs) enclosed in a thin metal casing with a cumulative part (CP) in the form of an inverted "V" (wedge shape, common in the USA), or "U" (semicylindrical shape, common in Ukraine), which enhances the effect of the explosion by concentrating it along the axis of the charge in a given direction (Fig. 1) [8, 9].

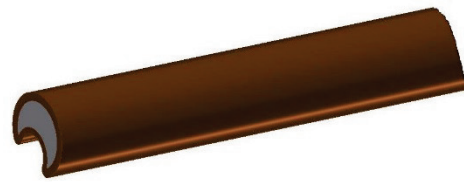


Figure 1 General view of a LSC with a semicylindrical cumulative part

The cumulative effect is achieved by using a charge with a shaped cavity directed towards the obstacle [10-12]. The schematic representation of a structural element of a launch vehicle SS with an installed LSC is shown in Fig. 2.

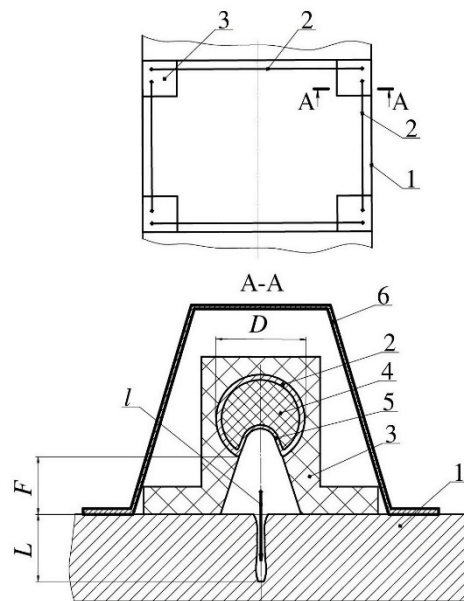


Figure 2 Schematic of a structural element of a launch vehicle SS with an installed LSC: 1 - LV body section (obstacle); 2 - LSC; 3 - LSC mounting bracket; 4 - LSC explosive; 5 - LSC cumulative part; 6 - Detonation product protection; l - cumulative jet; F - focal distance; L - penetration depth of the CJ

Focal distance is the distance between the obstacle and the LSC at which the cumulative jet reaches its maximum depth of penetration into the obstacle material. It is an important design parameter that affects the penetration depth of the CJ and, consequently, the separation efficiency.

Thus, determining the required focal distance is a key task in calculating the effect of cumulative charges and developing pyrotechnic separation systems based on LSCs [13-16].

Upon detonation of the explosive material (EM) in the LSC, a cumulative jet is formed. Individual elements of this jet will move normally to the surface of the cumulative part (CP) only in the immediate vicinity of the CP itself. As the jet propagates further, it will straighten in accordance with the general laws of gas dynamics. At a certain distance from the base of the CP, the cumulative jet will experience its maximum compression. This distance is defined as the focal distance (F), see Fig. 3. Beyond the focal distance, the cumulative jet rapidly degenerates due to the radial dispersion of the detonation products compressed to high pressure [7].

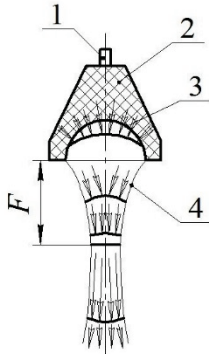


Figure 3 Schematic of the formation of a cumulative gas flow: 1 - detonator; 2 - explosive charge, 3 - semispherical cumulative part, 4 - cumulative gas flow

In general, the focal distance depends on the design of the LSC, the parameters of its cumulative part, the type and amount of explosive material (EM), the manufacturing accuracy of the LSC, and the characteristics of the obstacle, including its density. The focal distance increases with increasing EM charge power, increasing obstacle material density, and manufacturing accuracy of the cumulative charge [14]. At the optimal focal distance, maximum penetration of the CJ into the obstacle is ensured.

Optimal focal distance is the distance between the LSC and the obstacle that ensures maximum penetration of the cumulative jet into the obstacle material. The optimal focal distance can be determined experimentally or by modeling, taking into account various parameters such as the LSC design, obstacle material properties, and so on. The optimal focal distance allows for maximum separation efficiency of structural elements and, accordingly, increases the reliability and safety of rocket and space systems.

Recommended focal distance is the distance that is recommended for use in the design of separation systems. The recommended focal distance may differ from the optimal one depending on the specific conditions. Recommendations

may be based on previous research, standards, empirical data, or design considerations. They may include safety factors, ease of use, design features of the SS, technological limitations in the manufacture and installation of the LSC, operating conditions of the LV, etc.

The nominal value of the distance between the LSC and the obstacle should be equal to the optimal focal distance, but this is not always achieved in practice; as a rule, it is close to it. The recommended focal distance, in contrast to the optimal one, takes into account the tolerance field, determined by the manufacturing accuracy, thermal expansion of the structure during flight, and other factors.

It is important to select the recommended focal distance of the LSC taking into account all these factors. This can be achieved through theoretical calculations, experimental research, and computer modeling.

Aluminum alloys are widely used in the manufacture of LVs due to their lightness and sufficient strength. In Ukraine, there is currently a transition to the use of aluminum alloy 2219 due to its characteristics and capabilities for improving the efficiency of rocket and space technology. Thus, the use of aluminum alloy grade 2219 contributes to a reduction in the thickness of the shell structure of the LV body compartment, which results in an increase in the volume of tanks and the weight of the payload. Therefore, there is a need to determine the focal distance of the LSC installation on obstacles made of this alloy.

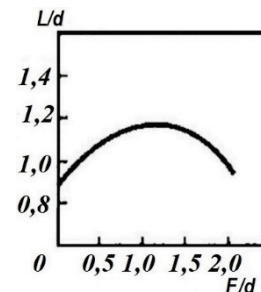


Figure 4 Dependence of the penetration depth of the CJ of a copper LSC with a semicylindrical CP, filled with hexogen, on the focal distance for a steel obstacle [7]: L - penetration depth of the CJ; d - diameter of the CP of the LSC; F - focal distance

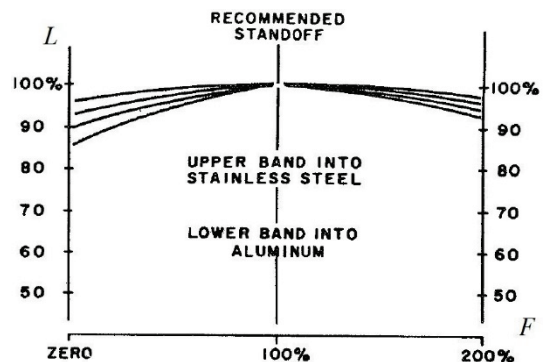


Figure 5 Penetration efficiency of the CJ of a lead LSC with a wedge-shaped CP, filled with hexogen, as a function of the focal distance [9]: F - Focal distance, in percent of the recommended value; L - Penetration depth of the CJ, in percent of the recommended focal distance; The upper graph shows the dependencies for a steel obstacle, the lower one - for an aluminum obstacle

Within the framework of this article, experimental studies are considered to determine the optimal and recommended focal distance of the LSC installation in the LV body compartment, made of aluminum alloy grade 2219, using a new method that allows you to reduce the number of tests and increase the accuracy of determining the focal distance.

The focal distance is a fundamental characteristic of the LSC [7, 10]. With a deviation of the focal distance from the optimal value, the penetration depth of the CJ decreases, in accordance with the results presented in Figs. 4 and 5.

According to [7, 12, 17, 18], as a result of a series of studies of copper LSCs on various obstacles, the following ranges of recommended empirical ratios are known F/D (see Tab. 1).

Table 1 Recommended ranges of empirical ratios F/D

Ratio F/D	Material of the obstacle	Source
1,0...1,5	Steel	Petushkov, L. P. [7]
0,7...1,1	Steel of various grades and titanium alloys	Yefanov, V. V. [17]
0,8...1,6	Aluminum and magnesium alloys	Yefanov, V. V. [17]
1,1...1,3	Aluminum alloys grades AmG6, D16	Linnik, A. K. [18]

Analyzing the data presented in Figs. 4, 5, and Tab. 1, it can be concluded that the recommended focal distance for the installation of the LSC is within a certain range of values, while the maximum penetration depth corresponds to the most effective (optimal) focal distance.

Relevance of the research. Determining the optimal and recommended focal distance for the installation of the LSC is an important task in the design of LV separation systems using new materials.

The purpose of the research is to determine the optimal and recommended focal distance for the installation of an LSC of a certain diameter with a semicylindrical CP for the effective separation of an LV structural element, which is an obstacle made of aluminum alloy grade 2219.

Research Objectives:

- 1) Develop a methodology for the experimental determination of the focal distance;
- 2) Conduct an experimental study to determine the focal distance of the LSC for an obstacle made of aluminum alloy grade 2219;
- 3) Measure the depth of penetration of the CJ into the obstacle for the corresponding focal distance;
- 4) Analyze the research results.

2 PROBLEM SOLUTION

2.1 Methodology for the Experimental Determination of the Focal Distance

To determine the focal distance of a cumulative pyrotechnic device (LSC), a new methodology has been developed that allows:

- Reducing the number of tests by setting the LSC at an angle to the obstacle. This enables more efficient utilization of resources and time during the experimental process.

- Enhancing the accuracy of focal distance determination by obtaining CJ penetration depth results for the entire range of focal distances under investigation. This provides a more comprehensive understanding of the relationship between focal distance and CJ penetration depth.

The experimental study involved the following sequence of actions:

- 1) **Manufacturing of the LSC, an obstacle made of aluminum alloy grade 2219, and LSC mounting elements.** The obstacle was fabricated with a thickness exceeding the anticipated CJ penetration depth by several times. Standardized cumulative charges manufactured at the Scientific and Engineering Center "Explosive Processing of Materials" of the Paton Institute of Electric Welding (Ukraine) were employed. Brackets were also constructed to enable the LSC to be mounted on obstacle samples with high precision and control of the focal distance between the LSC and the obstacle.
- 2) **Installation of the LSC on the obstacle of the research object.** To identify the optimal and recommended focal distance, the LSC was installed at an angle to the obstacle. This facilitated a more comprehensive evaluation of the impact of focal distance on CJ penetration depth.
- 3) **Experiment.** Initiation of the LSC explosive charge. This initiated the explosive process that resulted in the formation of the CJ.
- 4) **Measurement of the CJ penetration depth into the obstacle.** After each experiment, the CJ penetration depth into the obstacle was measured for the corresponding focal distance values. This provided data on the relationship between focal distance and CJ penetration depth.
- 5) **Data analysis.** Following the experimental studies, the obtained data were systematized and analyzed using analytical methods. This enabled the identification of patterns and trends in the data, leading to the determination of the optimal and recommended focal distance for the LSC.

2.2 Research Object

The experimental setup for the study is shown in Fig. 6. The test object consists of the following components:

- Linear shaped charge (LSC) with a copper shell of 5 mm diameter filled with explosive material (hexogen 11,5 g/m);
- Metal plate made of aluminum alloy grade 2219 with a thickness of 20 mm. The alloy has the following characteristics: tensile strength $\sigma_v = 436,4$ MPa, yield strength $\sigma_{0,2} = 323,6$ MPa, and relative elongation $\delta = 10\%$;
- Brackets for mounting the LSC and an electric detonator.

The shape of the LSC used in the experiment is standardized and corresponds to the manufacturer's

nomenclature. It is approximately cylindrical with a half-cylindrical cumulative part (see Fig. 7).

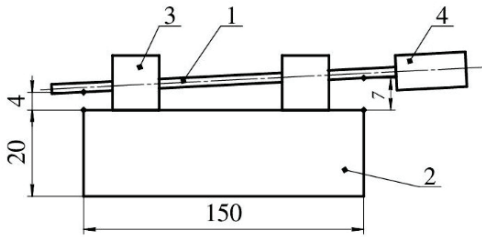


Figure 6 Scheme of the research: 1 - LSC; 2 - obstacle; 3 - LSC mounting brackets; 4 - electric detonator

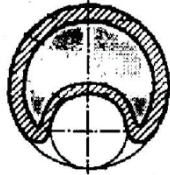


Figure 7 General view of the LSC with a semicylindrical cumulative part [7]

As shown in Fig. 6, the LSC (item 1) is mounted on the metal obstacle (item 2) using brackets (item 3) at a specific angle determined by the variation of focal distances within the investigated range. Based on the data presented in Tab. 1 and the analysis of the graphs in Figs. 4 and 5 - it was decided to conduct research in the range: $F/D = 0,8 - 1,4$, which corresponds to 4 to 7 mm for an LSC with a diameter of 5 mm. The LSC is detonated using an electric detonator (item 4) placed at the end of the LSC. The test specimen with the installed LSC is shown in Fig. 8.

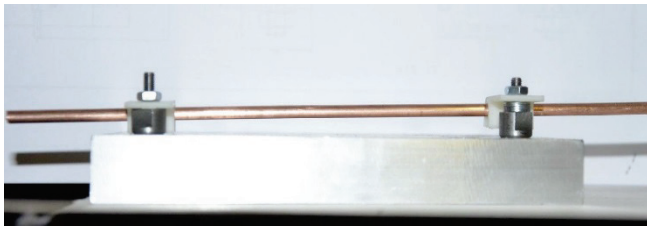


Figure 8 Test specimen made of aluminum alloy grade 2219

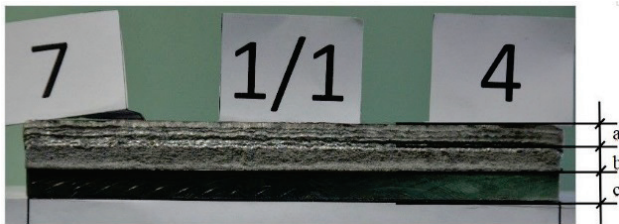


Figure 9 Cross-section of 2219 alloy specimens along the CS penetration line of the LSC: 1/1 – sample number in the numerator, test number in the denominator; 4 - designation of the minimum focal distance; 7 - designation of the maximum focal distance; a - trace of CJ penetration; b - trace of sample separation; c - trace of cutting with a disc cutter

To determine the penetration depth of the cumulative jet (CS), after testing, the specimens were cut from the reverse side of the CS action, along the LSC installation line, not reaching the CS penetration zone, and then one part of the specimen was separated from the other. After that, the depth

of CS penetration into the obstacle was evaluated using high-resolution photography (Fig. 9).

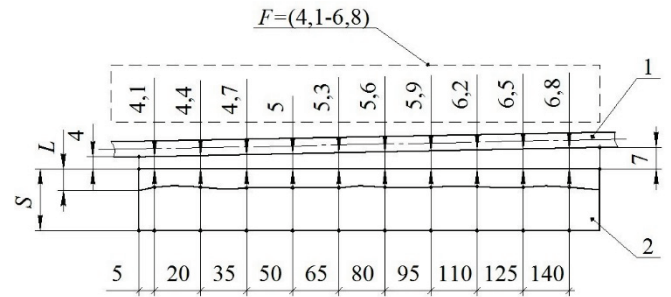


Figure 10 Measurement scheme: 1 - LSC; 2 - obstacle; S - obstacle thickness; L - measurement of CJ penetration depth; (5/20...140) - measurement points; F - range of investigated focal distances

To take measurements, photographs of the test specimen were imported into a CAD software package such as AutoCAD, where the required scale of the test specimen was obtained. After that, the CS penetration depth was measured according to the measurement scheme presented in Fig. 10. For each test, 10 measurements of the CS penetration depth (L) were made along the LSC obstacle cutting line at points from 5 to 140 mm (with a step of 15 mm).

2.3 Test Results

Three experiments were conducted. To improve the accuracy and reliability of the results, measurements were taken on both parts of each sample: Li.1 – corresponds to its first part, and Li.2 – to the second. The test results of the experiments to determine the dependence of the depth of penetration of the CJ on the focal distance of the installation of the LSC are presented in Tab. 2.

Table 2 Depth of CJ penetration of LSC into aluminum alloy grade 2219

Distance to the measurement point, mm	5	20	35	50	65	80	95	110	125	140
F	4,10	4,40	4,70	5,00	5,30	5,60	5,90	6,20	6,50	6,80
$L_{1,1}$	5,65	5,73	5,68	5,65	5,62	5,60	5,55	5,47	5,33	5,25
$L_{1,2}$	5,69	5,75	5,92	5,75	5,67	5,60	5,43	5,21	5,09	5,06
$L_{2,1}$	5,85	5,96	6,00	6,06	6,36	6,22	6,06	6,02	6,00	5,68
$L_{2,2}$	5,98	6,16	6,24	6,30	6,34	6,23	6,22	5,81	5,68	5,43
$L_{3,1}$	6,27	6,53	6,50	6,61	6,30	6,28	6,30	6,25	6,11	5,93
$L_{3,2}$	6,32	6,50	6,52	6,68	6,52	6,43	6,65	6,20	6,31	6,25
L_{min}	5,65	5,73	5,68	5,65	5,62	5,60	5,43	5,21	5,09	5,06
$L_{average}$	5,96	6,11	6,14	6,18	6,14	6,06	6,04	5,83	5,75	5,60
L_{max}	6,32	6,53	6,52	6,68	6,52	6,43	6,65	6,25	6,31	6,25

The results of the experiments in graphical form, showing the dependence of the focal distance on the depth of penetration of the CJ for the conducted experiments, are presented (see Figs. 11-12).

Fig. 11 shows the graphs of the dependence of the CJ penetration depth into the obstacle for each part of the sample ($L_{i,n}$). The penetration of the CJ demonstrates a uniform pattern in all conducted experiments. Minor deviations can be explained by the technological features of the LSC manufacturing process, including variations in the density of

the explosive substance in the casing and slight deviations in the geometry of the LSC cumulative part. This is confirmed by other studies that noted technological limitations could cause variations in the depth of CJ penetration up to 30% [14].

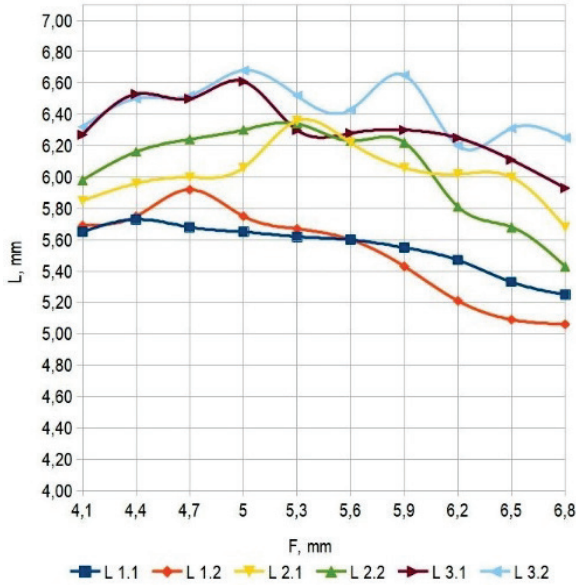


Figure 11 Dependence of focal distance on CJ penetration depth for conducted experiments: F – focal distance; L – penetration depth of CJ; $L_{i,n}$ – penetration depth of CJ, where i is the experiment number, n is the sample side number

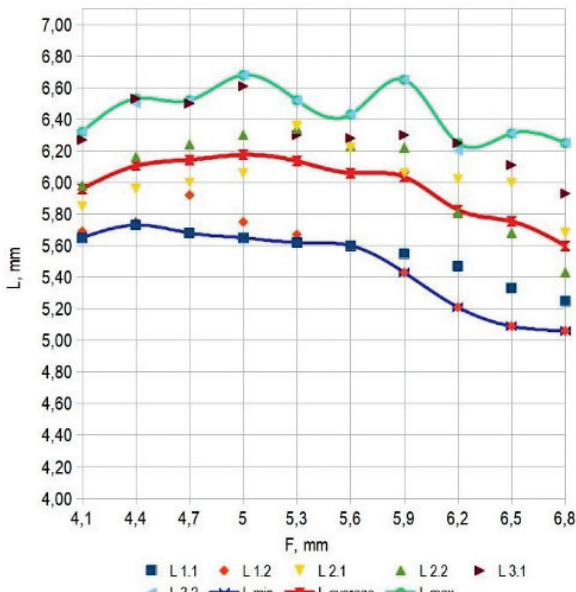


Figure 12 Dependence of focal distance on average, minimum and maximum depth of CJ penetration

For better data visualization, graphs were constructed to show the dependence of the average, minimum, and maximum CJ penetration depths on the focal distance, as shown in Fig. 12. The average line reflects the general trend, while the minimum and maximum values indicate the range of data distribution. The graphical representation of the average values is necessary to eliminate random deviations.

The graphs show that the penetration depth of the CJ initially increases with the increase in focal distance and then decreases. Thus, there is a certain dependence between the focal distance and the depth of penetration of the cumulative jet.

These graphs allow us to identify the correspondence to the empirical range of other researchers (see Tab. 1), but to accurately determine the optimal focal distance, it is necessary to establish a specific functional dependence.

2.4 Method for Establishing the Optimal Focal Distance

Graphically construct a polynomial function based on the average experimental values of CJ penetration into the obstacle. The construction process is best done in spreadsheets, such as LibreOffice, where a trend line should be constructed based on the average CJ penetration values, and the regression type should be selected as polynomial; the degree of the function should be chosen so that the approximation probability index R^2 is close to 1. An R^2 value that falls within the range (0,75 - 0,95) indicates a high level of correlation. After constructing the graph, a perpendicular should be dropped from the vertex of the function to the (x) axis, and the resulting value will be the optimal focal distance for the installation of the LSC.

The dependence of the depth of CJ penetration into the obstacle on the focal distance of the LSC installation, constructed based on the average values of CJ penetration depth, is shown in the form of a quadratic polynomial function in Fig. 13).

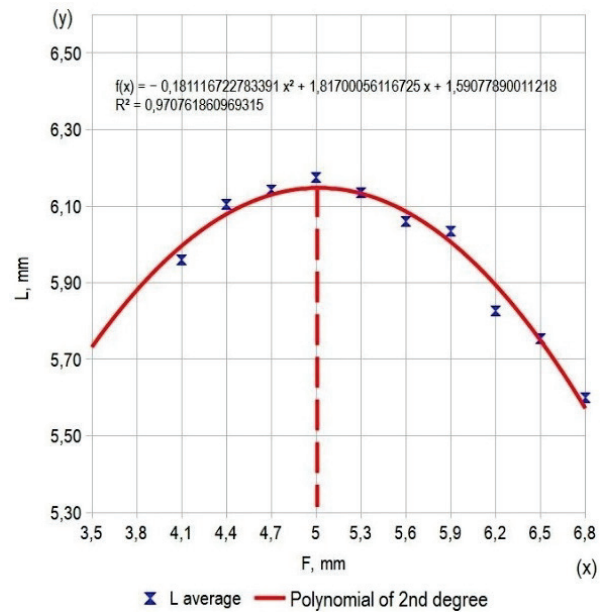


Figure 13 Dependence of the depth of CS penetration into the obstacle on the focal distance of LSC installation, represented by a 2-degree polynomial function (based on the average values of CJ penetration depth)

The choice of a second-degree polynomial function for approximating the data is justified, as it provides sufficient approximation accuracy and allows for easy determination of

the function's extremum. The approximation probability index $R^2 = 0,97$, indicates a high level of correlation.

The conducted research has established that the dependence of CJ penetration depth on focal distance follows a quadratic polynomial law:

$$f(x) = -0,1811x^2 + 1,817x + 1,5908. \quad (1)$$

Penetration depth of a 5 mm diameter cumulative jet into an aluminum alloy 2219 obstacle at focal distances ranging from 4,1 to 6,8 mm varies from 5,06 to 6,68 mm. The average penetration depth of the cumulative jet is 5,98 mm.

As can be seen from Fig. 13, the maximum penetration depth of the cumulative jet into the obstacle is achieved at a focal distance of 5 mm.

Comparison of the obtained result with the data from other studies showed that it corresponds to the empirical coefficients for aluminum alloys [17], where the optimal focal distance varies within $F/D = 0,8 - 1,6$. In our experiment for aluminum alloy 2219, this value was:

$$\frac{F}{D} = \frac{5}{5} = 1. \quad (2)$$

This confirms that the proposed methodology and research results correspond to the literature data and can be used in further developments.

The optimal focal distance for a 5 mm diameter LSC is $F = 5$ mm and provides a cumulative jet penetration depth of $L = 6,15$ mm. At focal distances of $F = 4,7 - 5,3$ mm, the cumulative jet penetration depth is $L = 6,13$ mm. The efficiency of cumulative jet penetration into the obstacle for the selected range of focal distances is 99.7%.

The nominal value of the distance between the LSC and the obstacle corresponds to the optimal value and is equal to 5 mm. The recommended range of focal distances for a 5 mm diameter LSC with a semi-cylindrical cumulative jet is $5 \pm 0,3$ mm.

The obtained values of LSC penetration depth and optimal/recommended range of focal distances are recommended for use in the design of new products where the obstacle is aluminum alloy 2219.

Thus, a comprehensive experimental study was conducted of one of the main parameters that determine the efficiency and reliability of the separation process - the range of focal distances of the LSC installation, which made it possible to increase the efficiency, reliability, and performance of pyrotechnic devices of the separation system of rocket and space elements.

3 CONCLUSION

A new methodology for the experimental determination of the focal distance was developed, which allows reducing the number of tests by installing the LSC at an angle relative to the obstacle and increasing the accuracy of determining the focal distance by obtaining results of CJ penetration depth for the entire range of focal distances under study. This

significantly reduces resource costs and the time for conducting experiments, which is an important advantage in resource-limited conditions.

An experimental study was conducted to determine the focal distance for a 5 mm diameter LSC with a semi-cylindrical cumulative part (filled with hexogen) on an obstacle made of aluminum alloy 2219.

The dependence of the CJ penetration depth into the obstacle on the focal distance of the LSC installation, which has a second-degree polynomial character, was obtained, allowing for optimization of the separation process by selecting the optimal focal distance.

As a result of the research, it was determined that with a change in focal distance from 4,1 mm to 6,8 mm, the penetration depth of the LSC cumulative jet into the obstacle material changes from 5,06 to 6,68 mm. The average penetration depth of the LSC cumulative jet is 6,11 mm.

A method for establishing the optimal focal distance is presented. The obtained value of the optimal (effective) focal distance of the LSC installation with a semi-cylindrical cumulative charge of 5 mm diameter is 5 mm; and the recommended focal distance is $5 \pm 0,3$ mm.

The research results provide valuable data for optimizing the mass characteristics of the structure by applying the optimal and recommended LSC installation parameter (focal distance). This will help in the development of more efficient and reliable separation systems in rocket and space technology. Optimizing the focal distance also helps to minimize mechanical loads on structural elements during the CJ penetration process into the obstacle.

The research results may be useful in the design of separation systems using new materials, such as composite materials or alloys with improved characteristics. Further experiments with new materials will expand the applicability of the proposed methodology.

Despite the successful results, this study has some limitations. It was conducted only for a specific type of LSC and obstacle material. For other types of LSCs or grades of obstacle materials, similar studies need to be conducted.

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