- Мигаленко К., Куценко М., Хряпак С., Школяр Є., Мотрійчук Р. / IMPROVING FIRE SAFETY OF METALIZED PYROTECHNICAL MIXTURES BY OPTIMIZING THEIR TECHNOLOGICAL PARAMETERS // Збірник наукових праць «Надзвичайні ситуації: попередження та ліквідація», Черкаси, НУЦЗУ 2025, - с.10.

UDC 614.841:536.46

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IMPROVING FIRE SAFETY OF METALIZED PYROTECHNICAL MIXTURES BY OPTIMIZING THEIR TECHNOLOGICAL PARAMETERS

The article presents a methodology for improving the fire safety of pyrotechnic products based on metallized mixtures with fluoroplastics. The main emphasis is placed on the influence of external thermal factors on key parameters, such as ignition temperature, induction time and probability of ignition source, as well as on the technical characteristics of the charges. The proposed method is aimed at optimizing the technological parameters of the mixtures, including the dispersion of the metal fuel, the excess oxidant coefficient, the compaction of the mixtures and the geometric features of the charges.

The results of the research demonstrate that regulating the composition of pyrotechnic mixtures allows to significantly increase their resistance to ignition under the influence of external heat. Reducing the risk of fire and explosion-hazardous destruction is achieved through the use of finely dispersed metal powders, as well as replacing magnesium fuel with aluminum, which significantly improves the fire safety of the products.

The application of the methodology allowed to increase the level of fire safety of pyrotechnic products both at the stage of their production and during transportation and storage. The results of the study create the basis for improving the regulatory framework and raising safety standards at Ukrainian enterprises.

***Keywords:** fire safety, pyrotechnic mixtures based on metal fuels and fluoroplastics, ignition and combustion development processes.*

Problem setting. Every year, pyrotechnic products designed to create special effects, such as thermal, sound, reactive, etc., are increasingly used in the economic sphere and military industry of Ukraine. This includes incendiary devices, solid rocket fuels, rocket and space technology devices, and others. The main components of such products are compacted mixtures of powders of metal combustible materials, such as magnesium, aluminum, titanium, zirconium, as well as fluoroplastics (F-3, F-4) and technological additives of organic and inorganic origin.

During transportation, storage or use of pyrotechnic products, they may be exposed to external thermal factors. In particular, these may be significant heating during fires in warehouses, thermal shocks during the launch or flight of products, as well as thermal effects during transportation. Such factors cause premature activation of charge mixtures, which accelerates their combustion and can lead to dangerous fire-explosive regimes.

Negative consequences are manifested in the destruction of product casings, which are accompanied by various fire factors: the release of flame, jets of high-temperature combustion products, casing fragments, incandescent particles of mixtures, sparks, etc. This can cause significant destruction of surrounding objects, loss of life and significant material losses.

The development of effective methods for preventing fire-hazardous destruction of products under the influence of external thermal factors is of significant practical importance. Such methods should be based on scientifically sound approaches that allow determining the critical parameters of external thermal influences on products, as well as technological characteristics of mixture compositions, the excess of which leads to premature destruction.

To create such methods, it is necessary to have the results of theoretical and experimental studies of the processes of thermal influence on the compositions of mixtures under various conditions (different heat flows, duration of their action, etc.), as well as ignition and combustion depending on external factors, such as elevated temperatures or pressures.

Today, the influence of technological parameters of charge mixtures, such as the ratio of components, dispersion, compaction coefficient, charge diameter, shell material and oxidizer humidity, as well as external conditions, including heating temperatures, pressures, humidity and composition of the environment, on the burning rate and explosive modes of their development is studied in scientific articles, monographs and research works.

However, systematic research and analysis of these results from the point of view of practical application at Ukrainian enterprises remain insufficiently developed. In particular, there is a lack of recommendations for improving the organization of fire protection systems at facilities where pyrotechnic products are used, especially in conditions of external thermal influences.

Analysis of recent research and publications. The relevance of the study is due to the need to prevent premature ignition of metallized pyrotechnic mixtures under the influence of external thermal load. Information on the temporal characteristics of the combustion of metal particles — such as magnesium, aluminum and zirconium — in gaseous environments is scattered and fragmentary, which complicates the creation of a manageable database for predicting fire-hazardous scenarios.

In [1], the fundamental mechanisms of thermal decomposition and combustion of metallized systems are considered, which allows us to assess the influence of magnesium and aluminum on the duration of combustion and the formation of high-temperature products. The study [2] focuses on the fire hazard of pyrotechnic products under external thermal influence, in particular based on fluoroplastic mixtures, and offers methods for predicting the duration of particle burning. In [3], the influence of mechanical characteristics of charges on their flammability is analyzed, which is important for assessing the parameters of thermal decomposition. In [4], detailed data on the combustion of aluminum powder are provided, and in [5], thermodynamic calculations of the temperature of combustion products are provided, which allows us to model the reaction rate. In [6], the conditions that cause premature ignition are considered, and in [7], a model of the development of the combustion process of mixtures with metal fuels and oxides is proposed, which provides accurate prediction of the time characteristics.

Based on the analysis of these sources, a method that combines mathematical modeling, experimental research results and applied software - three application program packages (APP1–PPP3) that implement modern numerical methods [1; 2] was formed. These programs allow in real time and dialogue to form a data array containing critical parameters of external thermal effects (intensity of heat flows, duration of their action) on pyrotechnic products created on the basis of the studied mixtures. In addition, they provide analysis of the main parameters of the combustion process of charge mixtures - the temperature of combustion products, the content of high-temperature condensate and the burning rate.

The method also takes into account the technological characteristics of the mixtures: the ratio of components, their dispersion, compaction coefficients and geometric dimensions of the charges. Exceeding the critical values of these parameters can lead to premature ignition, transition to explosive combustion and subsequent fire-hazardous destruction of products.

Thus, the solution to the problem is to create a scientifically based analysis and forecasting system that integrates the physicochemical, thermodynamic and structural parameters of pyrotechnic mixtures and allows you to effectively prevent premature ignition under conditions of external thermal load.

The purpose of this work is to establish quantitative relationships between key technological parameters (fuel dispersion, oxidant excess coefficient) of metallized pyrotechnic mixtures and their fire safety indicators (ignition temperature, induction time, probability of activation) for scientific justification of measures to reduce risks during their operation.Problem statement and solution.

To achieve this purpose, the following tasks must be solved:

– to analyze the influence of technological parameters – the oxidant excess coefficient (α) and the average particle size of the metal fuel (d_m) – on the ignition temperature (T_i) and induction time (τ_i) for mixtures of Mg + Ф-3 та Al + Ф-3.

– to adapt the methodology (based on DSTU 8828:2019) for quantitative assessment of the probability of occurrence of an ignition source ($Q_{\partial з}$) in pyrotechnic products under the influence of external heat.

– to establish the quantitative dependence of the probability ($Q_{\partial з}$) on the studied technological parameters (α, $d_м$) and the type of metal fuel (Mg vs Al).

The tasks are solved by modeling thermal effects, analyzing phase transitions in combustion products, and assessing the stability limits of the combustible environment, taking into account the design features of the facility. The results obtained allow for the formation of scientifically substantiated recommendations for increasing the efficiency of the fire and technogenic safety system.

Presentation of the main research material. The complex of created mathematical models in combination with the experimental data base constitutes the main component of the conducted research. The developed models and the formed base provide the possibility of obtaining and systematizing data arrays by critical parameters. It is these parameters that became the basis for developing a method aimed at preventing premature ignition and preventing the dangerous development of combustion processes.

In the center of the scheme is a generalizing block - "Mathematical models and experimental data base", which is the basis of the integrated analysis system. This block combines the results of theoretical calculations and experimental studies, which allows obtaining reliable information about the regularities of the process flow and more accurately determining the critical parameters of their development.

The first direction of the complex's work includes the development of mathematical models for calculating the processes of surface and volumetric transformation of matter. Thanks to these models, the modeling of physicochemical reactions that occur during heating or combustion of materials is carried out. This makes it possible to determine the main parameters - ignition temperatures, reaction rates, process stability limits and critical conditions under which the system may transition to a dangerous state.

The second direction involves the use of an experimental data base, which serves to check, refine and verify the obtained calculation results. The base contains the results of numerous experiments, which allows statistical analysis, comparison of theoretical dependencies with real measurements and correction of model parameters. Such interaction between theory and practice ensures high reliability and accuracy of predicting the behavior of the studied systems.

The third direction has applied significance and is focused on the practical use of modeling results. In the interactive mode, the user can form critical data sets, analyze and predict the development of processes, and assess the possibility of dangerous situations. This creates conditions for prompt decision-making aimed at improving safety, optimizing technological parameters, and preventing accidents.

Summarizing, it can be noted that the complex of mathematical models and the experimental data base form an effective system that combines analytical and practical approaches to the study of

combustion processes. Its use provides a deep understanding of the mechanisms of thermal and chemical transformations, allows for accurate determination of critical limits, and contributes to the development of scientifically sound methods for preventing dangerous situations.

A specialized software package (SPC) was used to increase the performance of calculations based on the described models. This package includes standard application packages (SAP1–SAP3), which provide the implementation of basic numerical methods for solving complex problems (see Fig. 2).

The software package includes three specialized application packages (SAP), which contain 60 modules created on the basis of modern numerical methods [1, 13]. Its effectiveness was confirmed by conducting large-scale numerical experiments: 200 engineering and technological problems related to the combustion processes of pyrotechnic mixtures were solved in an interactive mode.

The complex operates in DOS and Windows operating systems. To start the package, it is necessary to activate the corresponding executable file (for example, PAP1.exe, PAP2.exe, etc.), and exit is carried out by pressing the F10 key (in some cases, ESC or EXIT). The assignment of function keys is displayed in the bottom line of the screen, which simplifies management.

All numerical methods implemented in the packages are written in the Turbo Basic algorithmic language. They have been tested on a large number of examples (10–15 tests for each method), which cover typical engineering and technological tasks related to the combustion of pyrotechnic mixtures. As experiments have shown, the calculation times for test examples vary from several seconds to several minutes.

The application program packages (PAP1, PAP2 and PAP3) are presented in the format of bootable modules. The PAP1 package implements numerical regression and interpolation methods, PAP2 specializes in methods of numerical integration of functions, and PAP3 provides solutions of differential equations using numerical methods.

Algorithm for practical use of the method

At the first stage of the algorithm, basic initial information is generated. It includes:

– parameters of external thermal influence: heat flux density q_n, duration of its action t, heating temperature T_0, as well as pressure P, at which the combustion process of mixtures begins.

– echnological parameters of charge mixtures: type of oxidizer and metal fuel, oxidizer excess coefficient α, average particle size of metal fuel d_m and oxidizer particles $d_{ок}$.

– mechanical and thermophysical characteristics of mixtures: geometric shape and dimensions, density, heat capacity and thermal conductivity coefficient.

All this information is integrated with a set of mathematical models, an experimental database and specialized application packages (PAP1–PAP3) that are part of the SPC. This ensures the execution of calculations in interactive and real-time mode on personal computers..

At the second stage of the algorithm, the values of $T_з$ (the surface temperature of the mixture charge) and T_i (the ignition temperature of the metal fuel in the products of oxidizer decomposition) are entered. If the temperature T_s перевищує T_i, which corresponds to critical external thermal effects ($q_n > q_n^*$, $t > t^*$), this leads to accelerated self-heating of the mixtures, their premature ignition, explosive development of combustion, and, as a result, the destruction of pyrotechnic products. At the next step, a model of external thermal effects on the mixture charge is selected, after which calculations of the parameter values T_s are performed using specialized PAPs. These calculations are compared with the limit values for determining the critical indicators q_n^* and t^*, exceeding which causes destruction of products. In addition, surface temperature T_s measurements and heat flux q_n, at individual points of the charge are carried out. The obtained experimental data are compared with the calculated results to assess the errors of the methods for calculating the critical parameters q_n^* and t^* in real operating conditions. In the case of significant discrepancies between the experimental and calculated data (more than 10 – 12%), the models are corrected to ensure their accuracy.

At the third stage, the values of key parameters are entered, such as T_c (temperature of combustion products), g_c (relative content of high-temperature condensate) and u (burning rate of mixtures), as well as their critical limit values: τ_c^*, T_c^*, g_c^*, $u^*_{(\alpha)_{ВМГ}}$ (burning rate of mixtures at the upper concentration limit, exceeding which causes unstable, explosive combustion) and $u^*_{(\alpha)_{НМГ}}$ (burning rate of mixtures at the lower concentration limit, exceeding which leads to a sharp extinction of combustion). These parameters determine the possibility of ignition, extinguishing of mixtures, the level of fire hazard for surrounding objects in the process of developed combustion, as well as areas of instability that cause either rapid extinguishing or explosive combustion modes. After that, the appropriate mathematical model is selected, and with the help of specialized PAPs, the parameters T_c, g_c and u are calculated at given values of the controlled parameters (α, d_m, $d_{ок}$, T_0, P). The obtained calculated parameters are compared with their limit values, checking the fulfillment of the conditions: $T_c < T_c^*$, $g_c < g_c^*$, $u < u^*_{(\alpha)_{ВМГ}}$, $u > u^*_{(\alpha)_{НМГ}}$. If the specified conditions are not met, the values of the controlled parameters are adjusted and the critical ranges of their changes are determined. This includes: $\alpha < (\alpha)_{ucl}$, $\alpha > (\alpha)_{lcl}$, $d_м < d_м^*$ (або $d_м > d_м^*$), $d_{ок} < d_{ок}^*$ (або $d_{ок} > d_{ок}^*$), $T_0 > T_0^*$ (або $T_0 < T_0^*$), $P > P^*$ (або $P < P^*$). Then, selective measurements of the parameters T_c, g_c and u, are carried out, which are compared with the calculated values. Based on this, the errors of the calculation methods are determined to assess the critical ranges of changes in the controlled parameters. In the case of significant discrepancies (more than 10 – 12%) between the calculated and experimental data, the models are refined to increase their accuracy.

It is worth noting that the proposed scientifically based method allows in the process of developing pyrotechnic products made on the basis of mixtures of metal fuel powders and fluoroplastics, to create an array of data in an automated mode. This array contains critical parameters of external thermal effects and key characteristics of the combustion process of mixtures, the excess of which causes premature ignition of charges and unstable development of combustion. Such processes can lead to explosive destruction of products and the appearance of various fire hazard factors.

To reduce the risk of ignition and explosive destruction of pyrotechnic products during storage or transportation under conditions of external thermal influence, it is important to prevent the formation of centers of exothermic oxidation of metal particles in the combustible environment, which are formed during the decomposition of fluoroplastics. This can be achieved by using charge mixtures with a reduced level of flammability, which is ensured by optimizing their technological parameters.

Such parameters include the ratio of components, dispersion of components, compaction coefficient, as well as geometric characteristics of the charges, including their diameter, height and shape. Correct adjustment of these parameters allows minimizing the risk of dangerous self-heating and ignition of charge mixtures even under conditions of elevated temperatures or prolonged thermal exposure, which significantly increases the safety of storage and transportation of products.

To quantitatively assess the level of fire safety of products under conditions of external thermal exposure, a method based on the provisions of DSTU 8828:2019 is used. The document describes the general requirements for ensuring fire safety (paragraph 7) and the methodology for determining the probability of a fire occurring at a facility (paragraph B. Method for determining the probability of a fire occurring, paragraph B.3.4. Calculation of the probability of an ignition source).

This method allows to calculate the probability Q_{is} of occurrence of an ignition source in one pyrotechnic product, which can initiate the process of premature combustion of mixtures of product charges. It takes into account the impossibility of predicting in advance the specific conditions under which external influence on the surface of products can occur during their transportation or storage. In such situations, ignition sources can arise in the composition of mixtures due to foci of exothermic oxidation of metal particles in decomposition products of other components.

These processes often cause ignition of mixtures, which, in turn, leads to fire-hazardous destruction of products. The method of calculating the probability Q_{is} is a key tool for risk analysis

and prevention of critical situations. According to DSTU 8828:2019 (paragraph B.3.4, formula (B.30)), the following mathematical expression is used to determine the probability Q_{is} of the occurrence of an ignition source

$$Q_{is} = 1 - e^{-\tau/\tau_{is}} \#(1)$$

This expression for Q_{is} is calculated taking into account the storage or transportation time of the pyrotechnic product during the analyzed period of time, denoted as τ. The average time to the occurrence of an ignition source $\tau_{оз}$, is determined by the formula: $\tau_{is} = 3{,}03 \cdot 10^4 \cdot E_0^{1,2}$, where E_0 – is the minimum energy required to ignite a compacted mixture of components, J. The value E_0 describes the minimum energy required to heat the reaction zone of the c-phase of the mixture from the initial temperature T_0, K to ignition temperature T_i, under the influence of external thermal factors:

$$E_0 = \rho_c \cdot c_c \cdot \Delta V_c (T_i - T_0) \#(2)$$

where ρ_c, c_c – respectively, the charge density of the mixture (kg/m³) and its specific heat capacity (J/kg·K); ΔV_c – volume of the reaction zone of the k-phase of the mixture (m³), within which complete thermal decomposition of the oxidant and exothermic oxidation of metal particles occur, leading to ignition of the mixture.

Given that the charge has a diameter D, and the thickness of the reaction zone of the k-phase is equal to δ_1, in the first approximation the volume of the reaction zone ΔV_c can be defined as:

$$\Delta V_c = \frac{\pi \cdot D^2 \cdot \delta_1}{4} \#(3)$$

Substituting expression (3) into expression (2), we obtain an updated formula for further calculations.

$$E_0 = \frac{\pi \cdot D^2 \cdot \delta_1 \cdot \rho_c \cdot c_c}{4} \cdot (T_з - T_0) \#(4)$$

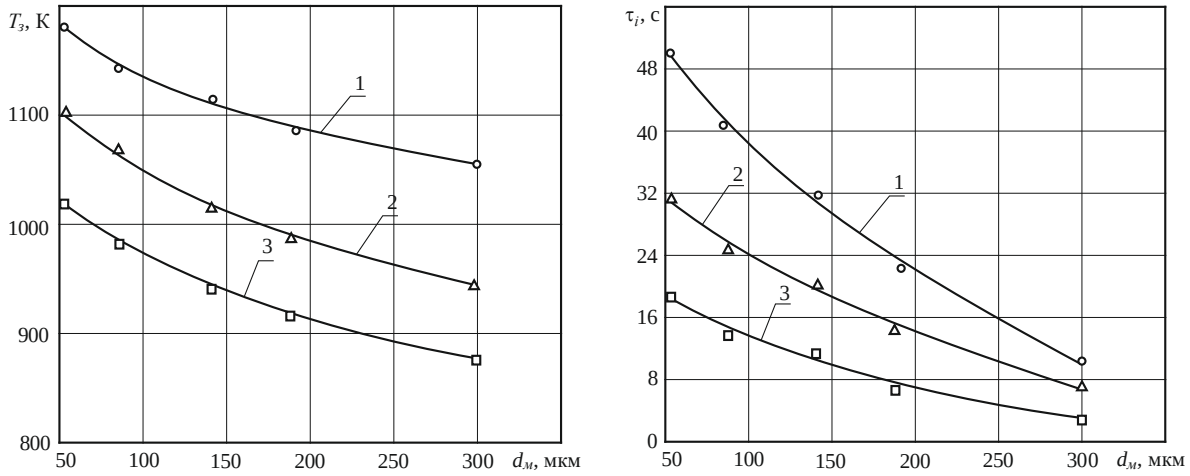
According to the established combustion mechanism of the pyrotechnic mixtures under consideration [1, 2], the value δ_1, in the first approximation, is defined as a parameter characterizing the thickness of the reaction zone of the k-phase of the mixture, within which the key process of thermal decomposition of the oxidant and exothermic oxidation of metal particles occurs.

$$\delta_1 = \frac{2R \cdot T_n \cdot a_0^2}{E_1 \cdot u} \#(5)$$

where R – gas constant, J/mol·K; T_s – surface temperature of the burning mixture, K; a_0^2 – thermal conductivity coefficient of the mixture, м²/с; u – combustion rate of the mixture, m/s; E_1 – енергія активації процесу повного термічного розкладання Ф – 3 при $T = T_n$, як основного sources of active gaseous products ($E_1 >> RT$), kJ/mol. According to the obtained experimental data [1, 2] (for $\alpha = 0{,}5 \ldots 0{,}6$ and $K_Y = 0{,}96 \ldots 0{,}97$): $T_s = 1050 \ldots 1200$ K; $E_1 = 127{,}5$ kJ/mol; $a_0^2 = 3{,}7 \cdot 10^{-6} \ldots 11{,}8 \cdot 10^{-6}$ m²/s, value$\delta_1 = 60 \ldots 340$ μm, that is, in order of magnitude, corresponds to the average particle size of the powders used Mg ($d_м = 54 \ldots 305$ μm) та Al ($d_м = 56 \ldots 310$ μm).

To determine the ignition temperature (T_i) and the induction (delay) time (τ_i) experimental studies of the ignition processes of Mg + F – 3 and Al + F – 3 mixture charges were conducted. These studies were performed under conditions of external thermal influences under various technological parameters, such as the oxidant excess coefficient α, average particle size of metal fuel $d_м$ and oxidant d_N, the mixture compaction coefficient K_Y and the charge diameter D, which is shown in Figures 1 and 2.

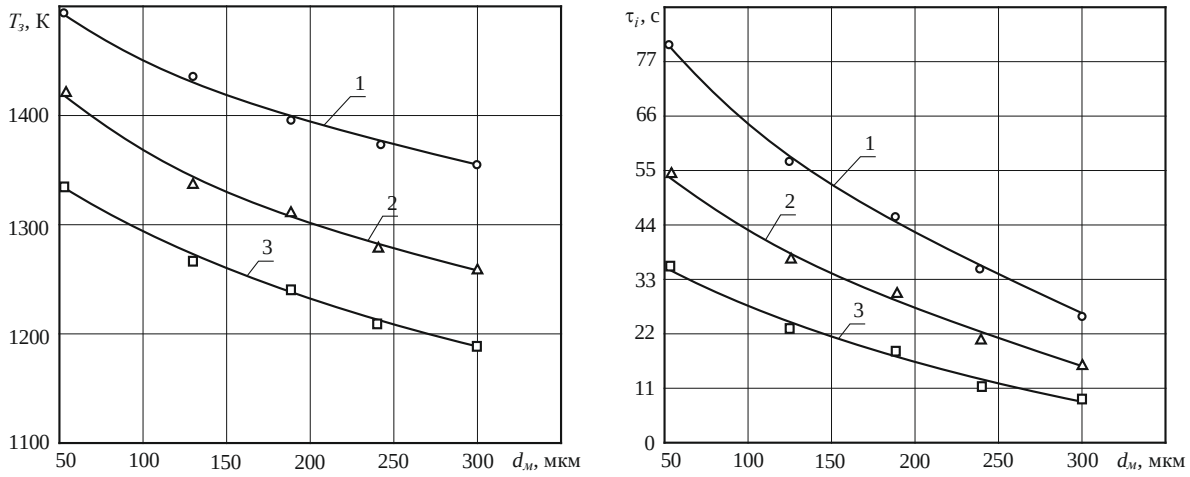
According to the data presented in Figures 1 and 2, the values of the ignition temperature $T_з$ and the induction time τ_i significantly depend on the concentration of the oxidant in the mixture and the dispersion of the metallic fuel. When the oxidant excess coefficient (α) from 1,5 to 0,5, as well as the particle size of the metallic fuel ($d_м$) from 305 μm to 56 μm (for magnesium) and from 310 μm to 54 μm (for aluminum), the value of $T_з$ increases by 1.4–1.9 times, and τ_i – by 2.7–3.2 times.



a) b)

Figure 1. Dependences of the ignition temperature (a) and induction time (b) of cylindrical charges of mixtures based on Mg + F – 3 from the average particle size of the metal fuel for the values of the oxidant excess coefficient α = 0,5 (1); 1,0 (2); 1,5 (3) ($d_{ок}$ =100 μm; $K_У$ = 0,96…0,97; D = 2…3·10^{-2} m; T_0 = 293 K; P = 10^5 Pa): ○, Δ, □ – experimental data.

As we can see from the dependences of Figure 1, to increase the fire safety of products during storage and transportation, where there is a risk of external heating, it is technologically advisable to use finely dispersed metal fuel powders and oxidizer-depleted (fuel-rich) formulations.



a) b)

Figure 2. Dependences of the ignition temperature (graph a) and induction time (graph b) of cylindrical charges of mixtures based on Al + F – 3 from the average particle size of the metal fuel for different values of the oxidant excess coefficient α = 0,5 (1); 1,0 (2); 1,5 (3) ($d_{ок}$ =100 μm; $K_У$ = 0,96…0,97; D = 2…3·10^{-2} m; T_0 = 293 K; P = 10^5 Pa): ○, Δ, □ – experimental data.

The data in Figure 2, especially when compared to Figure 1, provide a compelling scientific rationale for replacing magnesium fuel with aluminum fuel to improve fire safety. The choice of aluminum as a metal fuel is an effective fire prevention measure because it makes the pyrotechnic product significantly more resistant to external thermal influences.

Therefore, the use of finely dispersed metal powders at the stage of manufacturing pyrotechnic charges created on the basis of metallized mixtures with fluoroplastics and with an excess of metal fuel contributes to an increase in the time until their premature activation under the influence of external thermal influences. This, in turn, ensures an increase in the level of fire safety of pyrotechnic products manufactured using this technology.

To quantitatively assess the probability Q_{is} of initiating an ignition source under thermal action, which leads to fire-hazardous destruction of pyrotechnic products, calculations are used according to formulas (1)–(5). Using the example of two serial pyrotechnic products with different mixtures (Table 1), taking into account the obtained experimental data (see Fig. 1, 2) and the known physicochemical characteristics of the studied mixtures, the following was established: for product 1, the probability of Q_{is} with a decrease in α and d_m decreases by 2,1 – 2,7 times; для for product 2, the similar decrease in probability is 1,5 – 1,9 times.

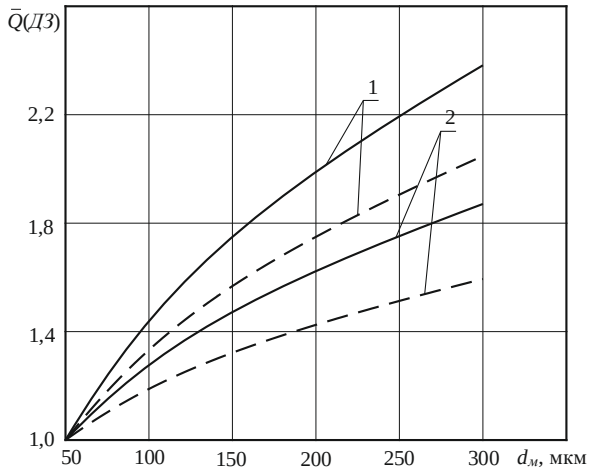


Figure 3. Relative probability dependence of $\bar{Q}(is)$ ($\bar{Q}(is)=\frac{Q(is)}{Q^*(is)}$, where $Q^*(is)$ is the probability value for the minimum particle size of the metal fuel used in practical ranges of changes [1, 2]) of fire-hazardous destruction of pyrotechnic products under external thermal influence. The probability depends on the dispersion of metal fuel powders and their content in mixtures used in pyrotechnic product charges. The first product with a charge based on Mg + F – 3; 2 is indicated by graph 1, he second product with a charge based on Al + F – 3 is indicated by graph 2 (see table 1); – ——— – mixtures with α = 0,5; – – – – – mixtures with α = 1,4 represent the dependences for the corresponding coefficients of excess oxidant.

Table 1 – List of pyrotechnic products for general industrial purposes, on the example of which the probability calculation methodology was tested Q_{is}

№	Purpose	Composition of the pyrotechnic mixture charge	Recipe for the main components of the pyrotechnic mixture charge	Relative mass content of the mixture components, %
1	Solid pyrotechnic fuels for ramjets	Mixture based on Mg + F – 3 + technological additives	F – 3	65
			Mg	31
			Technological additives	4
2	Pyrotechnic incendiary products	Mixture based on Al + F – 3 + technological additives	F – 3	69
			Al	28
			Technological additives	3

Thus, modification of the composition of pyrotechnic mixtures, in particular, changing the content of powdered metal fuels and their dispersion, allows to significantly increase the fire safety of products under the influence of external thermal factors – more than 1,4 – 2,3 times. In addition, replacing one metal fuel with another also contributes to increasing safety. For example, using aluminum powder instead of magnesium powder provides an increase in the fire safety of the product by 1,7 times.

Conclusions

As a result of the research and development of a scientifically based method, it was possible to significantly improve the fire safety of pyrotechnic products at all stages of their life cycle - from production to storage and transportation. The results of the work have important practical and theoretical significance, which is reflected in the following key conclusions:

– the analysis established that by adjusting technological parameters (oxidant excess coefficient α and fuel dispersion d_m), the ignition temperature (T_i) of the mixture charges was increased by 1,4–2,5 times and the induction time (T_i) was increased by 2,3–3,4 times, significantly enhancing fire safety.

– a methodology for the quantitative assessment of the probability of an ignition source ($Q_{дз}$) occurring under external heat was successfully adapted based on DSTU 8828:2019. This adaptation made it possible to calculate and compare the integral fire safety indicators for different product compositions.

– the quantitative dependence was established: optimizing the composition (using finely dispersed metal powders and lower α) reduces the probability ($Q_{дз}$) of fire-hazardous destruction by 1,5–2,7 times. Critically, it was proven that replacing magnesium (Mg) fuel with aluminum (Al) fuel provides a significant improvement, increasing the fire safety of the products by 1,7 times.

The developed method and database can be used as a basis for improving regulatory documents, implementing new safety standards and optimizing technological processes in the production, storage and transportation of pyrotechnic products in Ukraine. In the future, these results can be applied to the development of safe mixtures in other industries where ensuring the stability of chemical processes and minimizing the risks of ignition are important.

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ПІДВИЩЕННЯ ПОЖЕЖНОЇ БЕЗПЕКИ МЕТАЛІЗОВАНИХ ПІРОТЕХНІЧНИХ СУМІШЕЙ ШЛЯХОМ ОПТИМІЗАЦІЇ ЇХ ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ

У статті представлено методологію підвищення пожежної безпеки піротехнічних виробів, створених на основі металізованих сумішей із фторопластами. Основний акцент зроблено на вплив зовнішніх теплових чинників на ключові параметри, такі як температура займання, час індукції та ймовірність виникнення джерела займання, а також на технічні характеристики зарядів. Запропонований метод спрямований на оптимізацію технологічних параметрів сумішей, включаючи дисперсність металевого пального, коефіцієнт надлишку окиснювача, ущільнення сумішей та геометричні особливості зарядів.

Результати досліджень демонструють, що регулювання складу піротехнічних сумішей дозволяє суттєво підвищити їх стійкість до займання під впливом зовнішнього тепла. Зменшення ризику пожежовибухонебезпечних руйнувань досягається завдяки використанню дрібнодисперсних металевих порошків, а також заміні магнієвого пального на алюмінієве, що значно покращує пожежну безпеку виробів.

Застосування методології дозволило підвищити рівень пожежної безпеки піротехнічних виробів як на стадії їх виробництва, так і при транспортуванні та зберіганні. Результати дослідження створюють основу для вдосконалення нормативної бази та підвищення стандартів безпеки на підприємствах України.

***Ключові слова:** пожежна безпека, піротехнічні суміші на основі металевих пальних та фторопластів, процеси займання та розвитку горіння.*