

## COLORIMETRY METHOD FOR NITROCELLULOSE POWDER CHARGE MONITORING SYSTEM

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### Abstract

Nitrocellulose powders are unstable chemical compounds. Over time, the consumer properties of the powder charge can change so much that the charges will not only be unsuitable for their intended use, but also become dangerous for personnel and the barrel system. This is associated with the problem of establishing the terms of safe storage of powders and their operational suitability, the need for a constant system for monitoring their condition.

However, in developed NATO countries, there is practically no system for monitoring powder charges throughout their entire shelf life. Some countries have some components of the above-mentioned system, but its elements do not fully cover the entire spectrum of the state of powder charges.

For the monitoring system to work effectively, informative indicators are needed that allow determining the state of powder charges without the use of complex diagnostic equipment. One of such indicators is the color of the surface of the powder element.

In this study, an automated method for assessing the quality of nitrocellulose powder charges by the color of their surface for further use as intended was developed. The use of this method will significantly reduce the time of assessment and decision-making by experts, and eliminate subjectivity. In addition, the method will allow creating a database of powder charges for further monitoring of their condition throughout the entire life cycle.

To confirm the reliability and adequacy of the developed method, an experimental study was conducted. The study data showed that the proposed hypothesis is true, namely, during storage, nitrocellulose powder charges change the color of their surface, and it is possible to determine their shelf life.

**Keywords:** nitrocellulose powders, storage, monitoring system, colorimetry, texture, color order index.

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## 1. Introduction

During storage, nitrocellulose powder charges undergo changes in their physical, chemical, energy and ballistic characteristics. These characteristics are determined by a number of properties and are assessed by the following indicators: powder density (charge mass changes), its combustion rate, powder strength, maximum powder gas pressure, initial projectile velocity, firing range [1–7].

Statistical data show [8–12] that the condition of powder charges determines the suitability of ammunition for its intended use, and therefore, further on, methods for monitoring the powder charge are considered.

Nitrocellulose powders are unstable chemical compounds. This leads to a constant change in the values of the above indicators. It is clear that over time, they, taken together, reduce the consumer properties of the powder charge. In the future, these properties can change so much that the powder charges will not only be unsuitable for their intended use, but will also become dangerous for personnel and the barrel system itself. Despite the war in Ukraine and the increase in ammunition supplies by NATO countries, the problem of storing ammunition in warehouses, both in Ukraine and around the world, remains relevant. There have been cases of unauthorized fires and explosions of gunpowder charges, which led to major disasters accompanied by human casualties [13–16].

The issues of organizing the storage of gunpowder charges are associated with the tasks of monitoring their condition. However, establishing warranty periods for the safe storage of gunpowder and their operational suitability is a complex problem that must take into account the process of changing their properties [17].

In some countries (Germany, Great Britain, France), there are certain mechanisms for checking the condition of gunpowder charges and ammunition in general [18]. However, there is practically no system, as such, for monitoring gunpowder charges throughout their life cycle. Where there are some components of the aforementioned system, its elements do not fully cover the entire spectrum of possible states of gunpowder charges and the corresponding control methods. The monitoring system includes the collection of informative indicators that allow one to judge the state of nitrocellulose based on the obtained data of their values by comparing the measured value with the specified criterion. Three components of the monitoring system are proposed: measurement (control of the measured value), state and forecast.

The measurement component includes indicators and methods for measuring these indicators. The state of powder charges is assessed based on the specified criteria. The forecast of the state of powder charges includes both the forecast of the state «without regeneration of powder charges» and the forecast of the possible state «with regeneration» at a specified point in time.

The following indicators are used: powder charge mass, initial projectile velocity, powder charge burning rate, maximum powder gas pressure, powder density and powder charge service life.

However, in addition to mass, the determination of all the listed indicators requires the use of laboratories with fairly complex diagnostic equipment and methods for determining the properties of powder charges. In this regard, it is of interest to search for indicators that do not require them. The indicator of the powder element surface color can be attributed to this type of indicator of the powder charge monitoring system. A number of publications [19–21] have shown the fundamental possibility of using colorimetry of nitrocellulose powder charges.

It should be especially emphasized that the colorimetry method is quite widely used to study the state of chemical products [22], but in the available sources, no information was found on its use for nitrocellulose powders.

According to [19, 23], when storing nitrocellulose powder charges, their color changes. This effect is noted in well-known studies [24, 25]. There is data on the assessment of the properties of powder charges based on their color change [19]. However, these studies were based on the method of expert assessments with the involvement of specialists who made a subjective decision. This approach has some disadvantages, which include:

- a long time required for analysis and decision-making by specialists;
- weak differences in color gradations raise questions about the correctness of the decision made.

Development of an automated method for assessing and inspecting a powder charge based on determining the color of its surface will eliminate these disadvantages. In addition, this will make it possible to create a database of powder charges and further control their condition throughout their entire life cycle.

To represent color in a computer, an abstract model is used in the form of a set of numbers, which usually consists of three or four values of color coordinates. Professional graphic programs usually use several color models [26], such as: RGB, HSB, CMYK, CMY, HLS, Lab, YIQ. Each of them has its own advantages and disadvantages.

The RGB color model is based on the principle of representing any color by adding three primary colors: red, green and blue. Each channel is characterized by a parameter (0–255), indicating the amount of the corresponding component in the final color. The color depth is calculated as follows: 3 channels with 8 bits each, i.e. 24 bits in total. This model most fully conveys the richness of the colors of the environment. It is also attractive because it does not require additional software. This is a sign of the universality of the tool.

The CMY model also uses three colors – Cyan, Magenta and Yellow. These colors describe the light reflected from white paper (based on subtraction) of the three primary colors of the RGB model. The disadvantage of this model is that all three color channels of the model must be used to form black. To eliminate this disadvantage, the CMYK model is used, i.e. a fourth channel, black, is added to the three basic colors. This leads to an increase in the amount of RAM, since the color depth is 24 bits and 8 bits actually encode brightness – a total of 32 bits. In addition, some colors cannot be described in the CMYK model, but are perfectly described by the RGB model. The CMY and CMYK models are used mostly for output to hard media. The HSB (Hue, Saturation, Brightness), HLS (Hue, Lightness, Saturation) color models are designed for working with color-transmitting equipment and are inconvenient for human perception. A cylindrical coordinate system is used, and the set of colors is one or two hexagonal cones. The color depth is represented by 24 or 32 bits. However, this model is much poorer in color representation than the RGB model. In addition, this model is hardware-dependent and does not correspond to the perception of the human eye.

The Lab color model is used as an intermediate color space for converting RGB to CMYK and vice versa, since it is not tied to a specific carrier. This color model has the maximum color gamut and the ability to adjust brightness without adjusting color.

Based on the above, the most suitable color model for solving the problem of automating the method of assessing and defecting powder charges based on color determination is the RGB model. This study proposes a method for assessing the quality of nitrocellulose propellant charges by the color of their surface for further use as intended. The use of this method will significantly reduce the time of assessment and decision-making by experts, and eliminate its subjectivity.

The aim of the study is to develop a method for assessing the quality of nitrocellulose propellant charges by the color of their surface as an element of the monitoring system of propellant charges to control their ballistic characteristics.

To achieve this aim, it is necessary to solve the following objectives:

1. Develop a method for assessing the quality of nitrocellulose propellant charges by the color of their surface.
2. Conduct experimental studies to verify the adequacy and confirm the reliability of the developed method.

## 2. Materials and methods of research

The object of the experimental research is the process of changing the color of the surface of the powder elements at different storage periods.

During the study, the main hypothesis was put forward, which is that during the storage of nitrocellulose powder charges, the color of the surface of the powder elements that make up the charge changes. This hypothesis of the study was tested experimentally by conducting a series of physical experiments.

The powder sample from one cartridge of ammunition consisted of 50 powder elements of seven-channel nitrocellulose powder. Visually, the color spread of the elements was determined from light brown to brown-black (**Fig. 1**).



**Fig. 1.** Sample of powder elements of seven-channel nitrocellulose powder

To determine the color of the powder elements, an Epson Perfection V19 scanner of A4 format was used. The powder elements were scanned with a resolution of 600 dpi. Output image data: uncompressed jpg format, color representation form – true color RGB with a length of 24 bits, image scale – 1:1.

In an experimental study to verify the reliability of the proposed method, powder charges with shelf lives of 6, 25 and 44 years were used.

The sample of powder elements consisted of 50 pieces of each year of manufacture. The experiment with powder elements of each shelf life consisted of 5 series of 10 elements. This made it possible to obtain more reliable results.

Using the developed method, the color of the powder elements is determined and based on this, their shelf life is predicted.

The data of the experimental studies were processed using the statistical processing method of empirical data [27]: checking for the presence of sharply outliers, reproducibility of experiments, and adequacy of the model.

The following assumptions were made when conducting the experiment and processing the experimental data:

1. In the initial state, all powder elements have the same color.
2. A change in color is a sign of a chemical reaction.
3. The storage conditions of the powder elements under study before the experiment are the same.

## 3. Results and discussion

### 3. 1. Method for assessing the color characteristics of the surface of nitrocellulose propellant elements

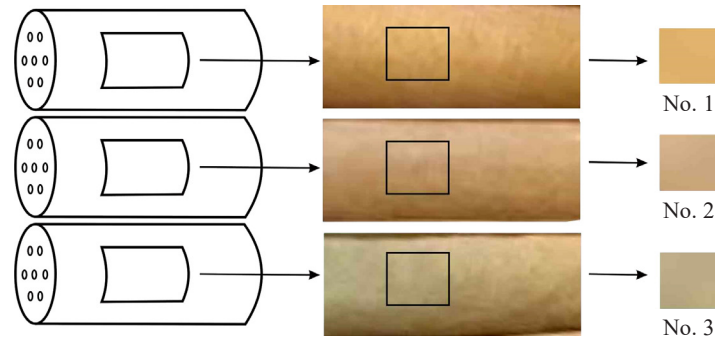
This method is based on the ability to select areas in a three-dimensional RGB color space that correspond to the prevailing colors for a given shelf life of the powder charge.

On each propellant element, a color assessment area was selected as a set of dots of a photo image. The size of the area for these propellant elements was specified as a rectangular frame with

dimensions of  $3.36 \times 3.78$  mm, which at the specified resolution corresponded to  $80 \times 90$  (7200) pixels. This area of pixels was called the texture of the propellant element [19].

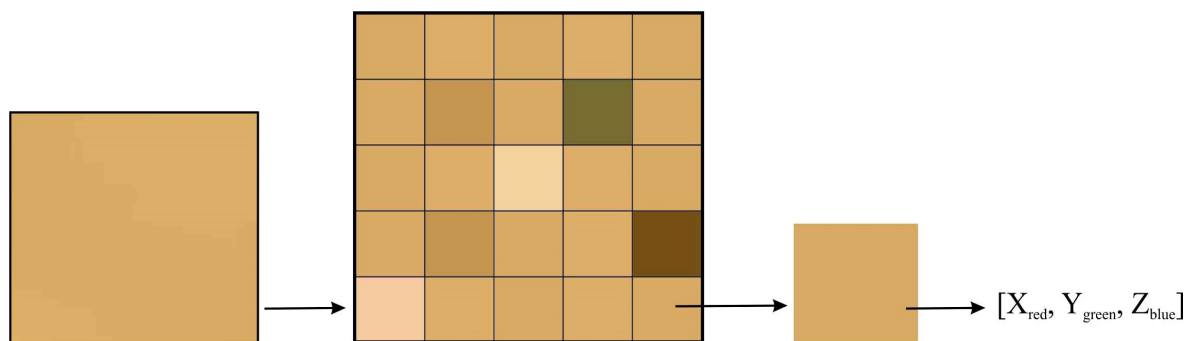
The process of selecting the texture of the propellant element is as follows (**Fig. 2**):

- the scanner projects the image of the propellant element onto the surface;
- the rectangular frame is located in the center of the propellant element;
- the texture properties of the propellant element are analyzed.



**Fig. 2.** The process of selecting textures of powder elements

For each powder element, the texture is presented as a set of pixels (**Fig. 3**).



**Fig. 3.** Representation of the texture of powder elements

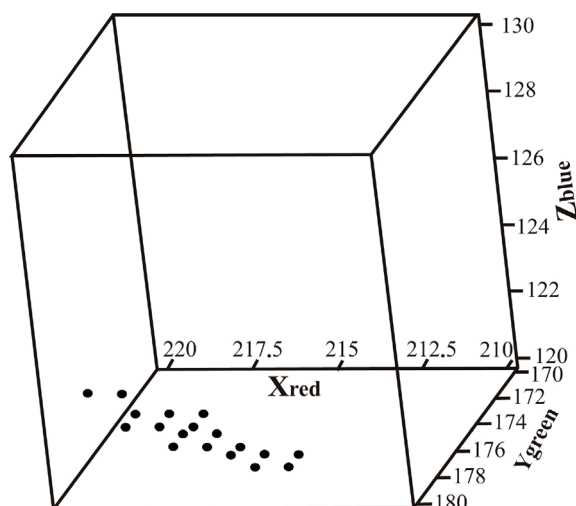
Each pixel is a combination of three scalar values  $X_{red}$ ,  $Y_{green}$ ,  $Z_{blue}$ , which characterize the basic colors of the RGB model (gradations of red, green and blue colors). These values are represented by an integer from 0 to 255, which corresponds to 256 gradations.

In the powder charge under study, the texture of the powder element is characterized by a set of shades of brown. For the adopted dimensions of the powder element texture (7200 pixels), it is necessary to construct separate histograms of the frequencies of the occurrence of gradations of the basic colors. Usually, these histograms have a form corresponding to the normal distribution law.

Next, all pixels of the powder element texture are checked for their location in the three-dimensional space of gradations of the basic colors, where the  $X$  axis is the axis of the red color gradation ( $X_{red}$ ), the  $Y$  axis is the axis of the green color gradation ( $Y_{green}$ ), the  $Z$  axis is the axis of the blue color gradation ( $Z_{blue}$ ).

The degree of compactness of the pixel arrangement shows a certain area of space, which corresponds to an «image» characterized by some parameter-features. Their analysis will allow to distinguish it from other «images» – to distinguish the texture of the powder element. An example of the result of three-dimensional visualization is shown in **Fig. 4**. A set of 7200 points (pixels) is located in a limited area (point cloud).

Next, a pairwise three-dimensional visualization of the textures of the powder elements is carried out – a comparison of the studied structure with the reference one. That is, the task of assessing the surface color of an individual powder element is reduced to the task of recognizing images in three-dimensional space.



**Fig. 4.** Visualization of the texture of the powder element in space

Thus, for each batch of powder charge it is necessary to:

- determine the color of the powder element that is at the warranty storage stage;
- determine the color of the powder element at the stage of expiration of the warranty storage period;
- determine the color of the powder element that is at the degradation stage (unfit).

This will allow creating reference areas in the color space for each category and sorting powder elements into high-quality and unfit.

Formalization of this method will allow automating the decision-making process for rejecting defective powder elements. This will also make it possible to determine the percentage of high-quality and defective powder elements in the entire tested powder charge and obtain data on the possibility of using it for its intended purpose.

Based on the conducted research, an indicator for possible sorting of powder elements was proposed – «color order indicator» [19]. The numerical values of the «color order indicator» are sorted by increasing (decreasing) the color intensity of each powder element and are its individual value (characteristic). When examining a powder charge, using the «color order indicator», it is possible to create a color scale by which to determine the shelf life of powder elements. And in such a scale, the indicators of the basic colors change in the ranges of not the entire spectrum, but only the possible colors of the powder element (from light brown to brown-black).

The principles of creating the «color order indicator» are as follows:

- a visual representation of the color of a powder element is a segment emanating from the origin of the RGB coordinates (OM) (Fig. 5);
- the brightness of the color increases with distance from the origin of coordinates;
- the set of possible values of the «color order index» of powder elements in a three-dimensional image will be a cone with the apex at the origin of the coordinate system and a base that has the form of a circle. The value of the «color order index» taking into account the resulting cone will determine the shelf life of the powder element.

The lighter the color, the greater the spread of color indices of the powder element and, accordingly, the larger the area of the cone section will be. As the shelf life of the powder element increases, its color becomes darker, the spread of color indices decreases, the base of the cone will decrease and, accordingly, the «color order index» will take a smaller value.

For any series of powder charge, it is possible to get a spread of color values that will be in the cone. The upper section of the cone will determine the shelf life. The higher the mean value of the «color order index», the shorter the shelf life.

The entire set of colors of the powder element is located inside this cone. When projecting the cone onto the planes  $XOY$ ,  $YOZ$ ,  $XOZ$ , it is possible to obtain sectors in which the projections of all colors are located.

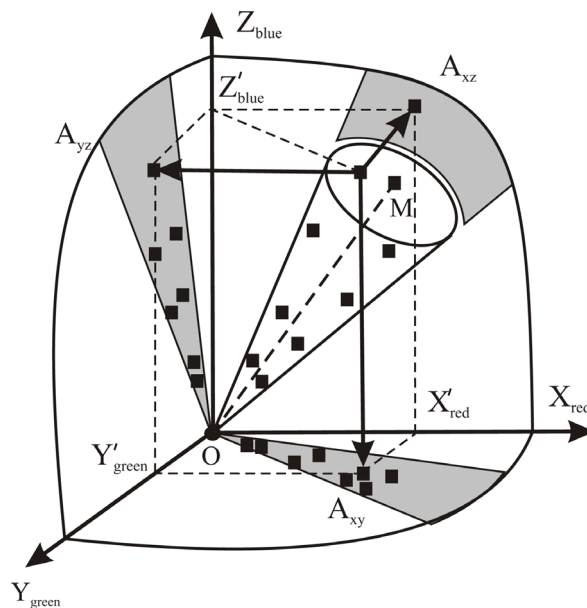


Fig. 5. Color order index

The numerical value of the introduced concept of «color order index» ( $K$ ) is represented by the relationship:

$$K = \sqrt{X_{red(mean)}^2 + Y_{green(mean)}^2 + Z_{blue(mean)}^2}, \quad (1)$$

where  $X_{red(mean)}$ ,  $Y_{green(mean)}$ ,  $Z_{blue(mean)}$  – mean values of red, green and blue colors of the given structure.

«Color order index» shows the distance by which the obtained point in three-dimensional space is from the origin of coordinates. The values of the color order index are sorted by any known algorithm from maximum values to minimum or vice versa.

Critically evaluating the developed model, it should be emphasized that the corresponding points of the «color order index» may not be on a straight line. However, the «color order index» itself is the mean color value at a given stage of the life cycle.

The developed approach, based on the change in the color of powder elements during storage under the influence of chemical reactions, is used as one of the methods for monitoring the state of the powder charge in the monitoring system.

However, it is worth considering the limits of applicability of this method. The main fact is that the geometric dimensions of the powder element must necessarily exceed the scanning frame (3.36×3.78 mm) several times, which is necessary to ensure the accuracy of the proposed method. Thus, this method is not applicable to single-channel granular powder, which is used in small arms cartridges. For practical application of this method, it is necessary to create a bank of color images of powder element series, i.e. to record their color during powder production. The color of the powder element of the produced series depends on a number of factors, for example, the characteristics of the raw materials used, and the features of the technology.

This study examines the use of the colorimetry method for storage periods of no more than 44 years. Extending the shelf life of powder elements requires further research, but the feasibility of such long storage periods is questionable.

### 3. 2. Verification of the adequacy and confirmation of the reliability of the developed method

The data from the examination of powder charges with shelf lives of 6, 25, and 44 years showed that the hypothesis put forward is valid, namely, during storage, nitrocellulose powder charges change the color of their surface.

As a result of the conducted research using the above-described method, data on the color gradations of the basic colors for each series of 10 powder elements were obtained.

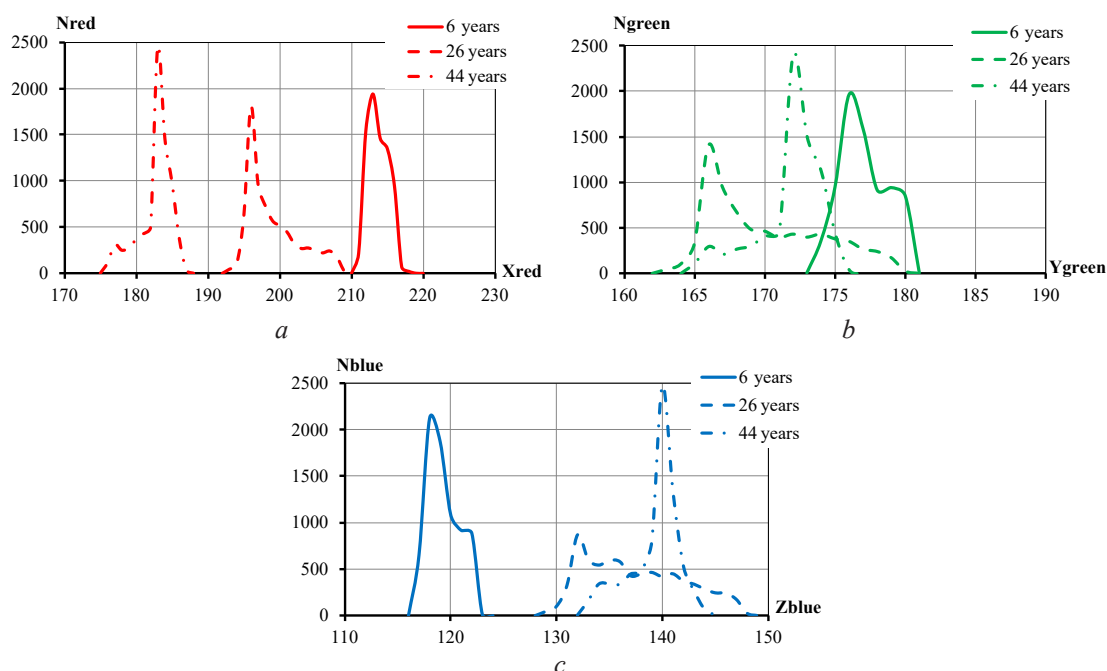
**Table 1** shows the results of one series of experiments to determine the color gradations of the basic colors of the texture of the powder element of seven-channel nitrocellulose powder 6 years of storage from one ammunition cartridge in the form of relative units.

**Table 1**

Results of the color gradations of the basic colors for the texture of the powder element of seven-channel nitrocellulose powder

| TPE number | Red color value – $X_{red}$ , rel. units | Green color value – $Y_{green}$ , rel. units | Blue color value – $Z_{blue}$ , rel. units |
|------------|------------------------------------------|----------------------------------------------|--------------------------------------------|
| 1          | 215                                      | 179                                          | 118                                        |
| 2          | 214                                      | 177                                          | 116                                        |
| 3          | 213                                      | 181                                          | 122                                        |
| 4          | 211                                      | 177                                          | 119                                        |
| 5          | 216                                      | 179                                          | 116                                        |
| 6          | 213                                      | 177                                          | 120                                        |
| 7          | 218                                      | 175                                          | 116                                        |
| 8          | 215                                      | 173                                          | 122                                        |
| 9          | 214                                      | 176                                          | 119                                        |
| 10         | 211                                      | 173                                          | 123                                        |

For the set values of the texture of the powder elements, histograms of the frequencies of occurrence of gradations of basic colors were constructed – separately for red, green and blue (**Fig. 6**).



**Fig. 6.** Histograms of distribution of gradations of basic colors: *a* – red; *b* – green; *c* – blue

Gradations of basic colors correspond to arguments  $X_{red}$ ,  $Y_{green}$ ,  $Z_{blue}$ . The nature of the obtained histograms shows the distribution of values  $X_{red}$ ,  $Y_{green}$ ,  $Z_{blue}$  near the three most frequently occurring values for each storage period (**Table 2**). When determining the gradations of maximum frequency, it became possible to generate an artificial color that corresponds to the natural texture of the powder element. This color is an analogue of the natural one (shown in the photo), but will have a gradation configuration with averaged values.

The mean results of color gradations of basic colors of 10 series of the experiment for each storage period of the powder charge are presented in **Table 2**.

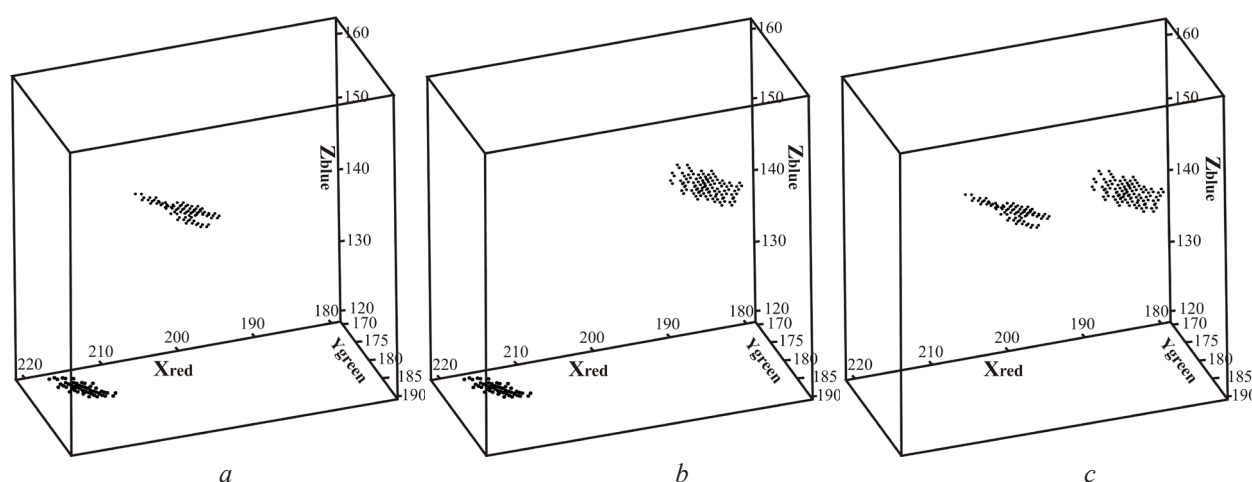
**Table 2**

Results of color gradations of basic colors for the texture of the powder element of seven-channel nitrocellulose powder

| Shelf life, years | Mean red color value – $X_{red(mean)}$ , rel. units | Mean green color value – $Y_{green(mean)}$ , rel. units | Mean blue color value – $Z_{blue(mean)}$ , rel. units | Color order index, rel. units |
|-------------------|-----------------------------------------------------|---------------------------------------------------------|-------------------------------------------------------|-------------------------------|
| 6                 | 214                                                 | 177                                                     | 119                                                   | 302.14                        |
| 25                | 199                                                 | 170                                                     | 137                                                   | 295.41                        |
| 44                | 183                                                 | 172                                                     | 139                                                   | 287.04                        |

It is clear that each year can be clearly divided by the red gradations – these curves do not intersect. There are zones in the green and blue colors where the presence of values of several storage periods is possible. But even in this case, with a certain probability, it is also possible to obtain the value of the storage periods of the powder charge. When analyzing the set of gradations of three colors, the ambiguity in the definition is almost completely removed.

A paired three-dimensional comparison of the textures of the powder elements of the studied storage years is shown in **Fig. 7**.



**Fig. 7.** Paired comparison of powder element textures: *a* – 6 and 26 years; *b* – 6 and 44 years; *c* – 26 and 44 years

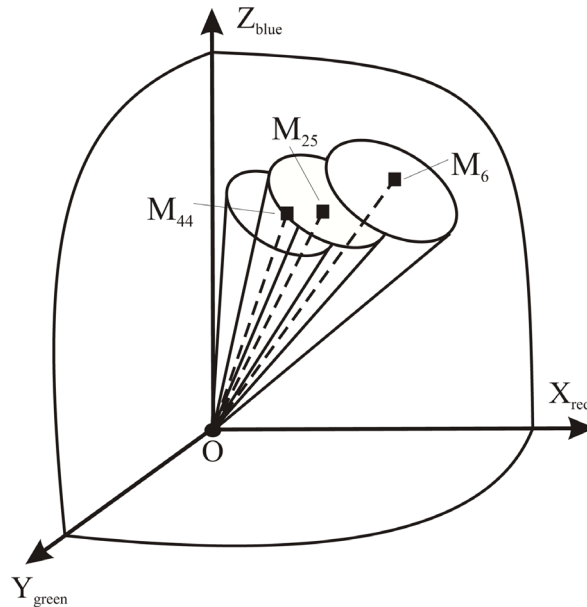
Its analysis establishes a certain pattern – the closer the powder element textures are in color, the greater the interpenetration of their clouds in one or more basic colors.

In **Fig. 7, a, b**, the three-dimensional visualization of the clouds of two textures has interpenetration in green, but differs in red and blue. In **Fig. 7, c**, the clouds of two textures have interpenetration in green and blue, but differ in red.

Based on this, it can be argued that determining the shelf life of powder charges in paired three-dimensional visualization is possible not only by three, but also by two or one basic colors.

Each series of the powder element, as can be seen from **Fig. 7**, will have its own cone of color tone values. The cones of different series of the powder element will differ in size and the angle of inclination of their symmetry axes to the center of the coordinate system.

A qualitative representation of the placement of such cones for series of powder charges of 6 years of storage, 25 and 44 years is shown in **Fig. 8**. In **Fig. 8**, segment OM6 is a visual representation of the reference color of the powder element of 6 years of storage, and its length corresponds to the value of  $K = 302.14$ . Similarly, segment OM25 corresponds to the reference color of the powder element after 25 years of storage with the value of  $K = 295.41$ , segment OM44 – the powder element after 44 years of storage and  $K = 287.04$ .

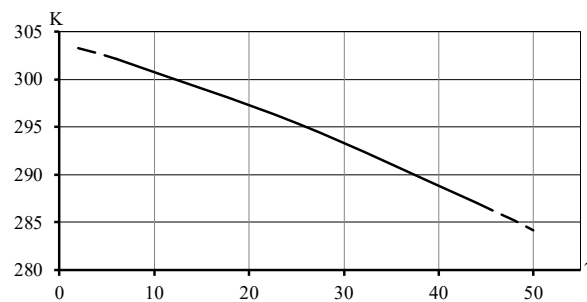


**Fig. 8.** Layout of «color order indicators» of powder charges with different storage periods

Based on the data in **Table 2**, a function was obtained for predicting the change in the «color order indicator» values depending on the storage period of the powder charge, the graph of which is shown in **Fig. 9**:

$$K = -0.23 \cdot 10^{-3} \cdot \tau^2 - 0.28 \cdot \tau + 303.92. \quad (2)$$

The decision on the belonging of the powder charge to a certain shelf life must be made in a complex, taking into account the value of the «color order index» and the distribution of color values by three channels.



**Fig. 9.** Dependence of the change in the values of the «color order index» on the shelf life of the powder charge

To correctly determine the shelf life using the proposed method, the ranges of values and the mean values of experimental data falling into them were determined.

In addition, the values of the 1<sup>st</sup> and 2<sup>nd</sup> type errors were determined for each considered shelf life.

The 1<sup>st</sup> type error is the probability that the powder element of a given shelf life was not determined as such. For example, a powder element with a shelf life of 6 years is not determined as a powder element with this period.

The 2<sup>nd</sup> type error is the probability that powder elements of other shelf lives are determined as specified. For example, powder elements with shelf life of 25 and 44 years can be defined as powder elements with a shelf life of 6 years.

Comparative results of real shelf life of powder charges and shelf life obtained by the described method are presented in **Table 3**.

**Table 3**

Comparison of the results of assessing the shelf life of powder charges based on the results of colorimetry

| Known (actual) shelf life, years                                                | 6             | 25           | 44            |
|---------------------------------------------------------------------------------|---------------|--------------|---------------|
| Number of measurements                                                          | 50            | 50           | 50            |
| Value intervals for forecast using colorimetry method, years                    | 4–8           | 23–27        | 42–46         |
| Number of measurements that accurately determined shelf life                    | 42            | 41           | 40            |
| Probability of correct determination of shelf life                              | 0.83          | 0.82         | 0.8           |
| Number of measurements that incorrectly determined shelf life (quantity/period) | 8 (6/25;2/44) | 9 (3/6;6/44) | 10 (2/6;8/25) |
| Probability of type 1 <sup>st</sup> type error                                  | 0.17          | 0.18         | 0.2           |
| Probability of type 2 <sup>nd</sup> type error                                  | 0.05          | 0.14         | 0.08          |

As can be seen, the error of the method increases with increasing shelf life.

According to the data obtained, it can be stated that the presented method is sufficiently accurate and efficient.

The algorithm for monitoring powder charges using the proposed method is as follows:

1. Selection of a control lot after production in the amount of 30 units.
2. Recording the initial state and obtaining a digital color portrait of the control lot.
3. The storage conditions of the control lot and the entire manufactured lot are the same.
4. Control of the condition of the powder charge is carried out:
  - after 10 years of storage (warranty period);
  - after 15 years of storage;
  - then every 3 years.
5. For the control, 3 units from the control lot are used for each control.

Thus, the developed method for monitoring the condition of nitrocellulose powder charges allows to recommend it for use in the monitoring system during a storage period of up to 40 years.

#### 4. Conclusions

The hypothesis about the change in the surface color of the elements of the nitrocellulose powder charge during storage has been experimentally confirmed.

A method for colorimetry of nitrocellulose powder charges has been developed using a digital portrait based on the RGB model, in which, unlike known methods, the human factor is excluded.

The monitoring system allows screening the state of nitrocellulose powder charges based on the colorimetry method to decide on their suitability or the need for more in-depth research.

The RGB model has been chosen as a model for determining the color of the powder element and the powder charge as a whole. The conditions for fixing the color of the elements using photo systems with sufficient resolution have been established. Scanning of the powder charge can be carried out not by individual elements, but as a whole, distributing them in a one-dimensional layer.

It has been established that the problem of assessing the state of the powder charge by the color of its surface, when using this technique, is reduced to the problem of pattern recognition in three-dimensional space.

The proposed color order indicator makes it possible to arrange the colors of the textures of powder elements based on their numerical values. This will allow comparing reference values with the results obtained at any stage of the life cycle of ammunition and developing recommendations for their further operation.

The use of the developed method will allow determining the state of the powder charge without ballistic and energy experiments. Also, when comparing the quality of determining color shades and the time of their sorting, the automated method has an advantage over the method of expert assessments.

As a direction for further research, it is worth considering expanding the range of types of powders under study – plate, tubular. In addition, further research is related to the development of the monitoring system in the direction of supplementing it with various methods, including express control methods.

#### Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

#### Financing

The study was performed without financial support.

#### Data availability

Manuscript has no associated data.

#### Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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