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Создан в целях освещения результатов исследований и реальных достижений по актуальным вопросам машиностроения, техносферной безопасности, современной металлургии и материаловедения. В журнале освещаются проблемы развития фундаментальных исследований и инженерных разработок в ряде важнейших областей технических наук. Одним из главных направлений деятельности журнала является интеграция в международное информационное пространство.

Журнал включен в перечень рецензируемых научных изданий, в котором должны быть опубликованы основные научные результаты диссертаций на соискание ученой степени кандидата наук, на соискание ученой степени доктора наук (Перечень ВАК) по следующим научным специальностям:

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2.5.21 – Машины, агрегаты и технологические процессы (технические науки)
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Research Article

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Comparative Analysis of Occupational Injuries Dynamics in Russia and the Republic of Crimea in 2017–2021

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Abstract

Introduction. One of the health-saving resources for the working population is the improvement of the occupational safety system and prevention of occupational injuries (OI). Systematic scientific research in this field remains relevant as it helps to understand the interrelationships between the causes and consequences of OI in different sectors of economic activity. In recent years, there has been a lack of research on the structure and dynamics of OI in the Republic of Crimea (RC), and its indicators have not been compared. The aim of this study was to conduct a comparative analysis of Crimean and all-Russian dynamics of occupational injuries over a five-year period from 2017 to 2021 in order to identify trends and develop strategies for improving production safety.

Materials and Methods. Methods of systematization of scientific literature on the issue of OI were employed. Statistical data on the state of OI in the Republic of Crimea and the Russian Federation were analyzed and compared. The results were graphically presented in the form of histograms. Additionally, the positions of the republic in the official ratings on compliance with labor legislation were taken into consideration.

Results. The analysis of statistics has made it possible to compare the structure and dynamics of OI indicators in the Republic of Crimea with similar data on the national average. Regional differences in occupational injury rates have been identified. In 2017–2021, the number of fatal injuries per 1 000 workers increased in the country, and in Crimea the problem was more acute than in the average for Russia. According to the results for 2021, construction was the most hazardous type of activity in the Crimean region, while mining was the most dangerous one in the Russian Federation. The relative rates of occupational injuries (per 1 000 employees) in the region were lower than the national average. At the same time, the proportion of fatal injuries in Crimea was 1.5–2 times higher than the national average. The highest level of fatal injuries in Crimea was recorded in 2018–2019, likely due to increased construction activity. Injury rates were increasing, while the costs of occupational safety measures were also rising. At the same time, in 2021, the amount of funds allocated to labor protection in Crimea was approximately 1.7 times lower than the similar national average (per employee).

Discussion and Conclusion. It is advisable to use data on occupational injuries in the Republic of Crimea to develop scientifically grounded recommendations for improving the regional occupational safety system. These results are partially influenced by the integration of Crimea and are presented in comparison with all-Russian indicators. Therefore, the findings of this scientific work can be applied more broadly when developing a strategy for labor protection in other regions of the Russian Federation.

Keywords: occupational injuries in the Republic of Crimea, the number of workers injured and killed at work, funding for labor protection measures

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Научная статья

Сравнительный анализ крымской и общероссийской динамики производственного травматизма в 2017–2021 гг.

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Аннотация

Введение. Одним из ресурсов здоровьесбережения работающего населения является совершенствование системы охраны труда и профилактики производственного травматизма (ПТ). Систематические научные исследования в этой области сохраняют актуальность, поскольку поясняют взаимосвязи причин и последствий ПТ в различных сферах экономической деятельности. В последние годы в Республике Крым (РК) не изучались структура и динамика ПТ, не сопоставлялись его показатели. Цель представленной научной работы — сравнительный анализ крымской и общероссийской динамики производственного травматизма за пять лет, в 2017–2021 гг. Новые данные должны стать базой для повышения безопасности производства.

Материалы и методы. Использовались методы систематизации научной литературы по проблеме ПТ. Анализировались и сравнивались статистические данные о состоянии ПТ в РК и Российской Федерации. Результаты графически представлены в виде гистограмм. Кроме того, учтены позиции республики в официальных рейтингах по соблюдению трудового законодательства.

Результаты исследования. Анализ статистики позволил сравнить структуру и динамику показателей ПТ в РК с аналогичными данными в среднем по стране. Выявлены региональные особенности ПТ. В 2017–2021 в стране росло число пострадавших со смертельным исходом в расчете на 1 000 работающих, причем в Крыму проблема стояла острее, чем в среднем по России. По итогам 2021 года самым травмоопасным видом деятельности в Республике Крым было строительство, а в РФ — добыча полезных ископаемых. Относительные показатели производственного травматизма (в расчете на 1 000 работающих) в регионе ниже, чем в среднем по стране. В то же время доля травм со смертельным исходом в Крыму в 1,5–2 раза выше среднероссийской. Самый высокий уровень летального травматизма в Крыму зафиксировали в 2018–2019 гг., что может быть связано с активизацией строительства. Показатели травматизма растут на фоне увеличения затрат на мероприятия по охране труда. При этом в 2021 году объем средств, направленных на охрану труда в Крыму, был примерно в 1,7 раза ниже аналогичного среднероссийского показателя (в расчете на одного работающего).

Обсуждение и заключение. Данные о производственном травматизме в РК целесообразно задействовать для составления научно обоснованных рекомендаций по совершенствованию региональной системы безопасности труда. Результаты отчасти связаны с интеграцией Крыма, даны в сопоставлении с общероссийскими показателями. Это значит, что итоги представленной научной работы можно использовать шире — при формировании стратегии развития охраны труда в новых субъектах РФ.

Ключевые слова: производственный травматизм в Республике Крым, численность пострадавших и погибших на производстве, финансирование мероприятий по охране труда

Благодарности. Авторы благодарят руководителя Управления Федеральной службы государственной статистики по Республике Крым и г. Севастополю Балдину О.И. за помощь в подготовке статьи. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и замечания, которые позволили повысить ее качество.

Для цитирования. Макаричева А.А., Ефимова В.М. Сравнительный анализ крымской и общероссийской динамики производственного травматизма в 2017–2021 годах. *Безопасность техногенных и природных систем.* 2024;8(2):7–16. https://doi.org/10.23947/2541-9129-2024-8-2-7-16

Introduction. In order to preserve the country's labor potential, it is necessary to maintain a high level of occupational safety (OS) and to improve preventive measures aimed at reducing the risk of occupational injuries (OI). Systematic scientific research in this area can help to better understand the causes and consequences of OI in various sectors of the economy.

Since 2014, when Crimea reunited with Russia, there have been significant changes in the region's economy. A new need has arisen for research on OI indicators as an element of the all-Russian OS system. Materials on OS issues published before 2014 were fragmentary, which proves the relevance of analyzing and introducing OI indicators into the scientific discourse in the Republic of Crimea (RC). These indicators are essential for the development of both theory and practice of industrial safety, as they reflect the processes of integration of the region's industries into the Russian OS system based on a modern regulatory framework.

Many studies are devoted to the analysis of individual OI indicators in the most traumatic industries — construction [1], agriculture [2], mining [3]. Key factors that lead to industrial accidents are determined [4]; measures to reduce occupational risks are discussed [5]. At the same time, many researchers note the problem of distorted statistics on OI and occupational diseases in Russia. A significant number of minor and moderate injuries are not reported and are not included in official statistics [6], which makes it difficult to accurately assess the socio-economic impact of such incidents [7]. Comparative OI studies across industry sectors worldwide emphasize the universal nature of risk factors and the underestimation of the number of accidents (AC) and the severity of their consequences [8]. Researchers agree that the OI complex nature, combined with changing working conditions and new occupational risks, requires constant monitoring and analysis of occupational safety indicators.

Comparative OI studies in new, developing regions of Russia, in particular in the Republic of Crimea, are of particular interest. In the first years after the republic became part of the Russian Federation, D.U. Abdulgazis [9] and E.N. Abiltarova [10] studied individual OI indicators at enterprises and organizations in Crimea. However, from 2017 to the present, the dynamics of indicators has not been studied, and no comparative analysis has been carried out. At the same time, such research is especially relevant in the context of a noticeable increase in economic activity, changes in the structure of the manufacturing sector and the domestic market. The significant increase in the rate of production activity in the region necessitates an examination of data regarding accident investigations, the specifics of injuries (including fatalities). It is crucial to analyze and interpret the facts, identify recurring patterns, and develop new strategies to prevent occupational health issues.

It is worth noting that there is insufficient knowledge of a wide range of issues, from the analysis of OI dynamics in the Republic of Crimea to innovative approaches to improving the system of prevention and training of specialists. This indicates the relevance and significance of the presented research.

The aim of the work was to conduct a comparative analysis of occupational injury rates in Crimea and Russia over a period of five years.

Main tasks:

– analysis of the regional OI structure and dynamics in 2017–2021;

– comparison of OI indicators in the Republic of Crimea with the average Russian;

– discussion of the possibility of using the results of the analysis to improve the OS system.

Materials and Methods. Methods of systematization of scientific literature on OI issues, as well as analysis and comparison of statistical data on occupational injury indicators in the Russian Federation and the Republic of Crimea were used. The statistical reports of the Federal State Statistics Service of Russia (Rosstat) and the Department of the Federal State Statistics Service (UFSGS) for the Republic of Crimea and Sevastopol for the period from 2017 to 2021 served as the basis for the analysis. The results were graphically presented in the form of histograms. In addition, two ratings of the Ministry of Labor of the Russian Federation were taken into account. The first one ranked the relevant regional executive authorities in terms of activities in the field of public administration of occupational safety and health. The second defined the positions of Crimea in terms of compliance with labor legislation.

Results

1. *Current state of occupational injuries in the Russian Federation and the Republic of Crimea.*

From the perspective of the research topic under discussion, the period from 2017 to 2021 was of particular interest. During this time, several important transformations occurred due to the increase in economic activity. Since 2020, there has been a slight decrease in it, which was associated with the pandemic of coronavirus infection and other circumstances.

Let us note a number of methodological limitations that need to be considered when conducting this and similar research. Firstly, Rosstat, the Federal Service for Labor and Employment (Rostrud) and the Social Insurance Fund (FSS) use various methods of accounting for industrial accidents. As a result, some generalized data do not match. Secondly, during this period in the region, private entrepreneurs did not take into account all cases of OI.

Thus, the Crimean and all-Russian indicators for 2017–2021 from the reports of Rosstat and the UFSGS for the Republic of Crimea and Sevastopol were studied. The analysis took into account direct data on the average number of employees, the number of victims of occupational accidents, including fatal ones. In addition, relative coefficient of the number of victims of occupational accidents (per 1000 employees), including fatal ones, was taken into account.

Information on the financing of OS measures at enterprises of the Republic of Crimea reflected the trends in the development of preventive measures in various industries.

At the first stage of the study, the Crimean and Russian average OI indicators for 2021 were compared. In 2021, in the Russian Federation, Rosstat recorded[1] 19,977,000 people employed at 158,264 enterprises from various fields of economic activity. By the end of the year, 93% of enterprises (147,630) reported no accidents. 21,609 people suffered injuries with disabilities (including fatalities), of which 30% were women (6,483). 1,210 people lost their lives as a result of serious accidents. Most of those who were fatally injured at work were men (93%).

According to the UFSGS data for the Republic of Crimea and Sevastopol[2], in 2021, 1,475 enterprises in the Republic of Crimea were subject to statistical accounting. Out of these, 1,400 (95%) did not have any accidents at the end of the year. The average number of employees of these enterprises was 181,773 people (9% of all those employed in production in the Russian Federation). 124 people were injured in work-related accidents with disabilities and fatal outcomes. Of these, 42 were women (34%). Fatal injuries were reported in nine cases, all of which were men.

In 2021, 93% of registered enterprises in the country and 95% in the Republic of Crimea did not record accidents. With regard to the total number of employees (in ppm of all employees in the Republic of Crimea), 0.68% suffered from disability in the Republic of Crimea, while the corresponding figure for the country as a whole was 1.08%.

The number of registered fatal accidents in the region accounted for 7.26% of the total number of work-related injuries. This figure was higher than the national average of 5.60%. The integral indicators for occupational injuries in the Republic of Crimea and Russia differed only slightly, so within the scope of this study, a separate analysis was conducted on occupational diseases by major economic activity.

Rosstat data[3] allowed us to identify the types of economic activity that were most affected by the number of fatal accidents in 2021. The table below shows the percentage of fatal accidents:

– manufacturing (22.6%);
– transportation and storage (16.5%);
– construction (15.9%);
– mining (14.8%);
– agriculture, forestry, hunting, fishing and fish farming (10.2%).

The number of people employed in various types of economic activity varied significantly, therefore, for a comparative OI analysis, it was advisable to use relative indicators per 1,000 people employed in a particular field. It was important to note that manufacturing employed about 25% of the average number of workers across the country, while mining employed only 5%, and this affected absolute OI indicators.

Mining was the leader among the types of economic activities recognized as injurious in Russia in 2021. Here, the number of victims with disability for one working day or more and with a fatal outcome amounted to 1.71 per 1,000 employees with an average of 1.08. Agriculture and forestry were in the second place (1.61). Activities in the field of culture, sports, leisure and entertainment took the third place (1.47). Construction was on the fourth place (1.35).

In the Russian Federation, the highest number of deaths due to work-related accidents was recorded in mining (0.18 per 1,000 workers with an average coefficient of 0.06), which was significantly higher than in construction (0.15) and agriculture (0.11).

In 2021, the Republic of Crimea reported the highest number of work-related injuries as a result of accident in construction. The OI coefficient for this sector was 2.72 per 1,000 employees and four times higher than the regional average (0.68). There were many injured persons in the field of water supply, waste collection and disposal (0.94), agriculture and forestry (0.88), mining (0.86) and manufacturing (0.79). The largest number of fatal injuries was recorded in construction and agriculture.

In Russia and Crimea, organizational problems were in the first place among the causes of accidents with serious consequences. This was evidenced by the results of labor protection monitoring[4]. Poor organization of production processes was the cause of every third accident with severe consequences, while the proportion of such incidents was constantly increasing.

[1] *Russian Statistical Yearbook. 2022*. Moscow: Federal State Statistics Service; 2023. 696 p. URL: https://rosstat.gov.ru/storage/mediabank/Ejegodnik_2022.pdf (accessed: 24.12.2023). (In Russ.).

[2] *Industrial Injuries at Enterprises and Organizations of the Republic of Crimea*. Department of the Federal State Statistics Service for the Republic of Crimea and Simferopol. Sevastopol. URL: https://82.rosstat.gov.ru/folder/27542 (accessed: 24.12.2023). (In Russ.).

[3] *Occupational Injuries in the Russian Federation in 2021*. Federal State Statistics Service. URL: https://rosstat.gov.ru/working_conditions (accessed: 24.12.2023). (In Russ.).

[4] *Results of Monitoring of Labor Conditions and Safety in the Russian Federation in 2021*. All-Russian Scientific Research Institute of Labor of the Ministry of Labor of Russia. URL: https://vnii-truda.ru/uploads/researches_file/659e9f020a8e7075635856.pdf (accessed: 24.12.2023). (In Russ.).

Minor but significant factors that contributed to occupational injuries include violations of traffic rules, poor labor discipline, and non-compliance with workplace safety standards. Approximately 7% of accidents with serious consequences were caused by deviations from the established technological process. Other reasons included shortcomings in the management and training of labor protection personnel, unsatisfactory condition and shortcomings in the organization of workplaces, refusal to use personal protective equipment. About a quarter of all accidents with serious consequences were difficult to classify unambiguously, as they were caused by circumstances that were not directly related to human error.

Thus, the comparison of OI indicators in the Republic of Crimea for 2021 revealed differences. When analyzing the basic integrated data, it appeared that the situation was fairly prosperous. However, a diversification of the Crimean indicators, in particular the distribution of victims per 1,000 employees in specific economic activities, indicated problems with ensuring security and the need for OS improvement.

Given the size of Russia, in order to correctly compare the average indicators for the country and the subject of the federation, many factors must be taken into account, including nature, climate, and technological development of the region. Comparable OI indicators made it possible to identify areas of increased risk and prioritize occupational safety measures.

2. *Analysis of the dynamics of occupational injury rates in the Russian Federation and the Republic of Crimea from 2017 to 2021.*

Figure 1 provides the dynamics of the number of injuries and deaths at enterprises in the Republic of Crimea and the Russian Federation from 2017 to 2021.

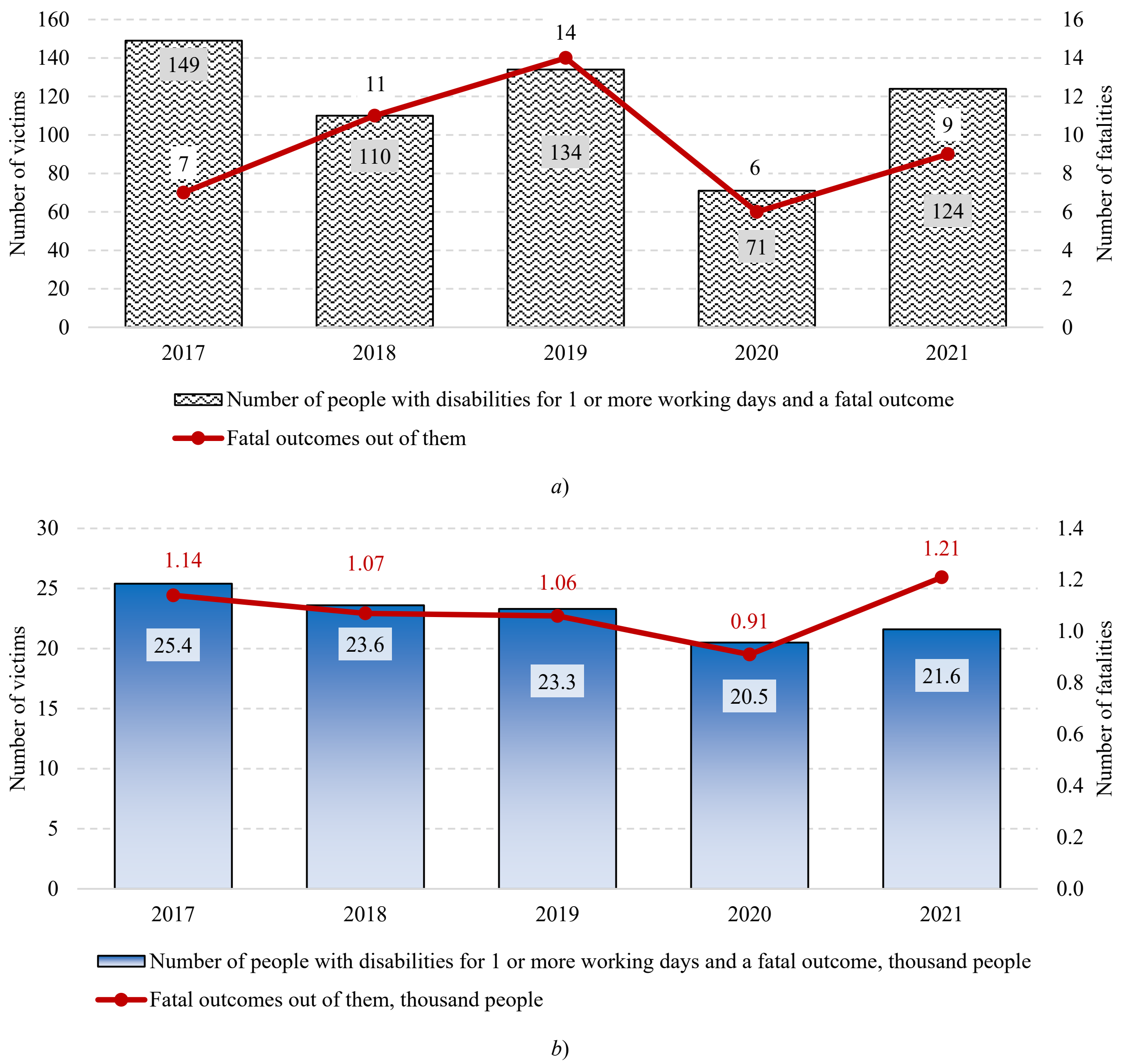


Fig. 1. Dynamics of occupational injury rates from 2017 to 2021:
a — in the Republic of Crimea; *b* — in Russia

Figure 1 shows how the main OI indicators have changed over the studied period. In the Republic of Crimea, the maximum number of victims of accidents was recorded at manufacturing enterprises in 2017 — 149 people. In 2018 it was 110 people, in 2019 it was 134. The minimum was recorded in 2020 (71 people), but in 2021 the figure almost doubled to 124.

The dynamics of fatal accidents was similar. The number of fatal injuries had been growing for two years, peaking in 2019, sharply decreasing in 2020 and increasing again in 2021 (Fig. 1 *a*).

In the whole country, the number of recorded occupational injuries had steadily decreased since 2017 (25,445 people), fell to a minimum in 2020 (20,503 people) and increased in 2021 (21,609 people). At the same time, the number of fatalities increased from 1,140 in 2017 to 1,210 in 2021. In 2020, the lowest number of deaths as a result of industrial accidents was noted (910, Fig. 1 *b*).

In 2017–2021, the proportion of fatal injuries in the Republic of Crimea significantly exceeded the average statistical indicators (Fig. 2).

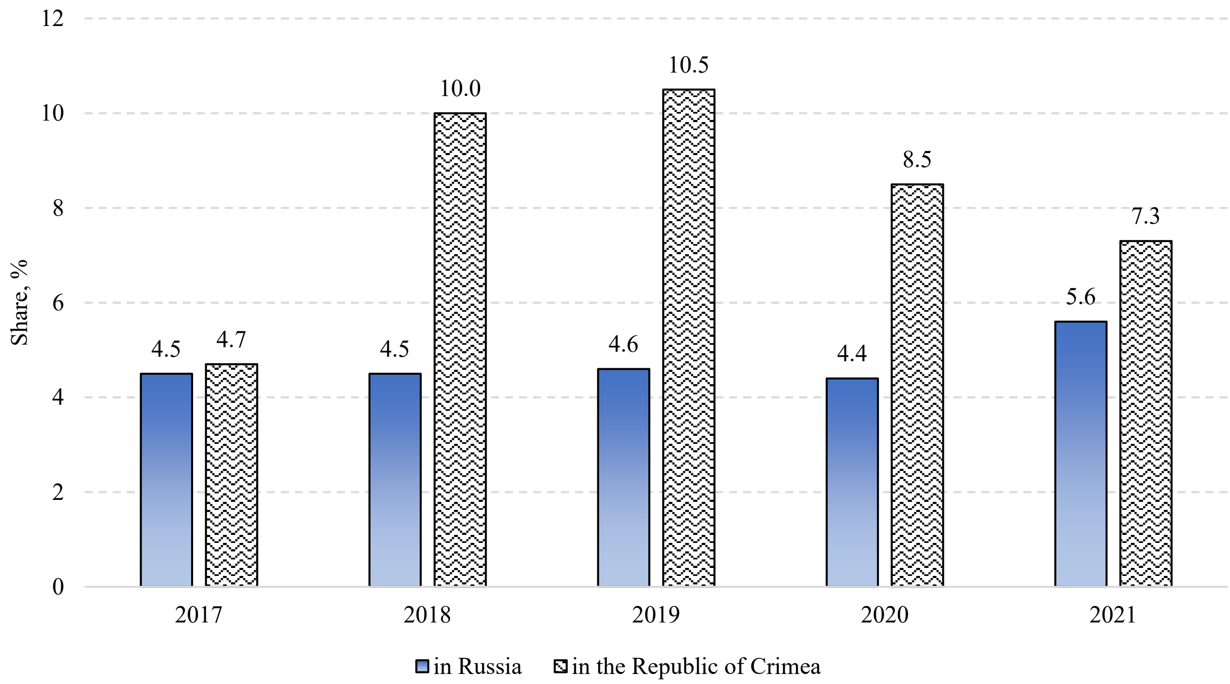


Fig. 2. Share of fatal injuries in Russia and the Republic of Crimea in 2017–2021, % of the total number of injuries

In 2018–2019, this indicator in Crimea was the highest and exceeded the national average by 2.2 times. This fact was probably related to the growth in construction volumes — this was the most traumatic type of economic activity in the region.

In the Russian Federation and Crimea, the situation regarding occupational injuries worsened in 2021 (compared to 2020) by three indicators:

– the total number of injuries at industrial enterprises increased (by 5% in the Russian Federation and by 75% in the Republic of Crimea);

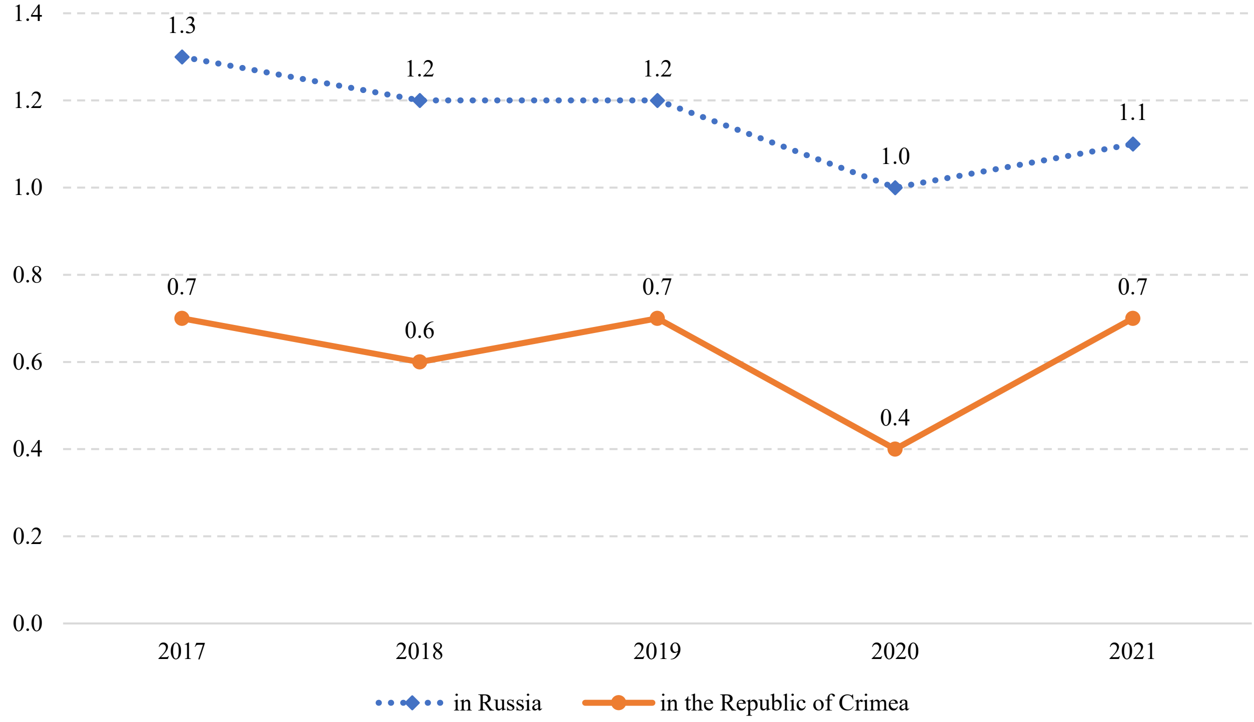
– there were more fatal injuries (by 33% in the Russian Federation and by 50% in the Republic of Crimea);

– the share of fatal injuries increased by 27% in the Russian Federation and decreased by 14% in Crimea (a sharp increase in the total number of victims was accompanied by a decrease in the proportion of fatal victims).

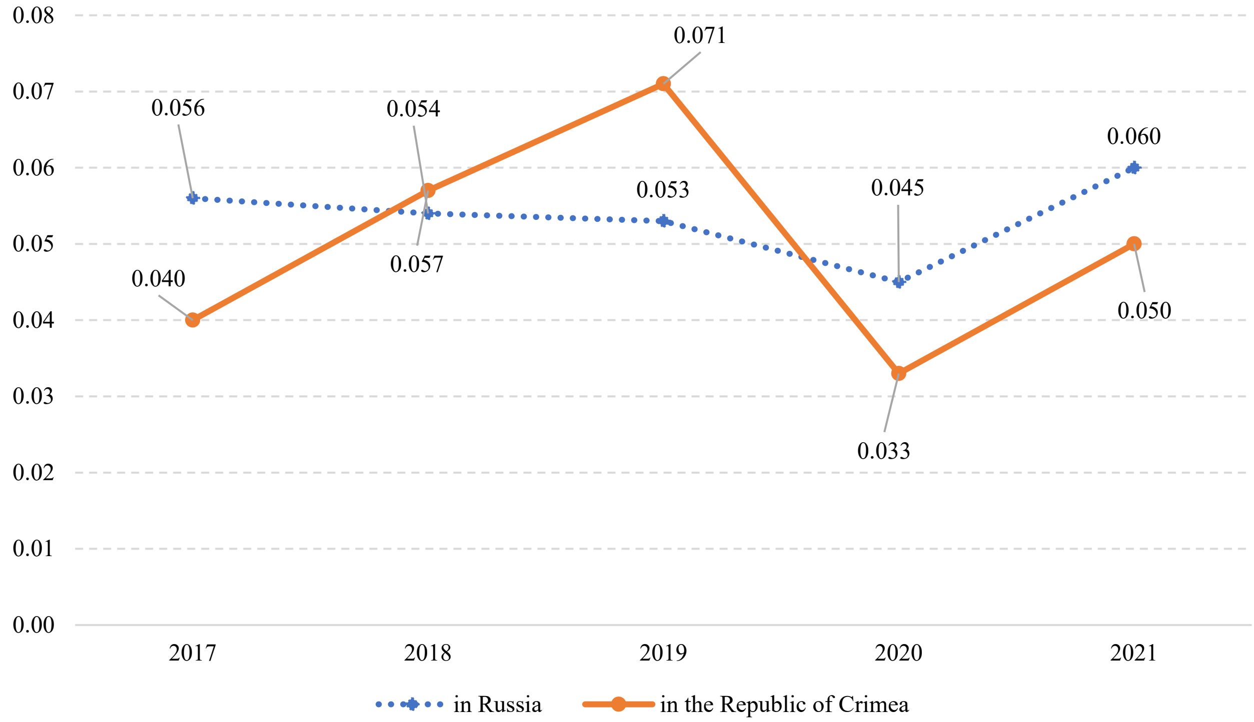
The high growth rates in the number of accidents in 2021 could be explained by the low base of 2020. Due to pandemic restrictions, injuries decreased significantly in 2020, leading to an unprecedented decrease in economic activity. Many industries saw businesses operating at reduced or partial capacity.

In general, in Russia in 2017–2021, the absolute number of victims with disability and death decreased by 18%. However, the number of deaths increased by 6% during this period. In Crimea, the number of people injured with disability also decreased by 18%. In 2021 (compared to 2017), the number of work-related deaths increased by 22%.

Let us consider relative Crimean indicators for victims with disability and death (per 1,000 employees). In this case, we used information on the types of economic activity included in the Rosstat sample. So, in 2017 and 2021, the same indicator was recorded — 0.7 people per one thousand employees (Fig. 3 *a*). However, the number of deaths per one thousand people employed in Crimea increased by 20%, and in Russia as a whole — only by 6% (Fig. 3 *b*).



a)



b)

Fig. 3. Dynamics of injury rates per 1000 employees in the Republic of Crimea and in Russia in 2017–2021:
a — victims with disability for one working day or more and with fatal outcome; *b* — victims with fatal outcome

Thus, the dynamics of the total number of occupational injuries in the Republic of Crimea corresponded to the all-Russian dynamics. However, a comparison of relative indicators showed that in fact the level of occupational injuries in Crimea remained unchanged over the years, and the level of fatal injuries increased more than in the whole country (Fig. 3). At the same time, funding for occupational safety measures in both the Russian Federation and in the Republic of Crimea increased (Fig. 4).

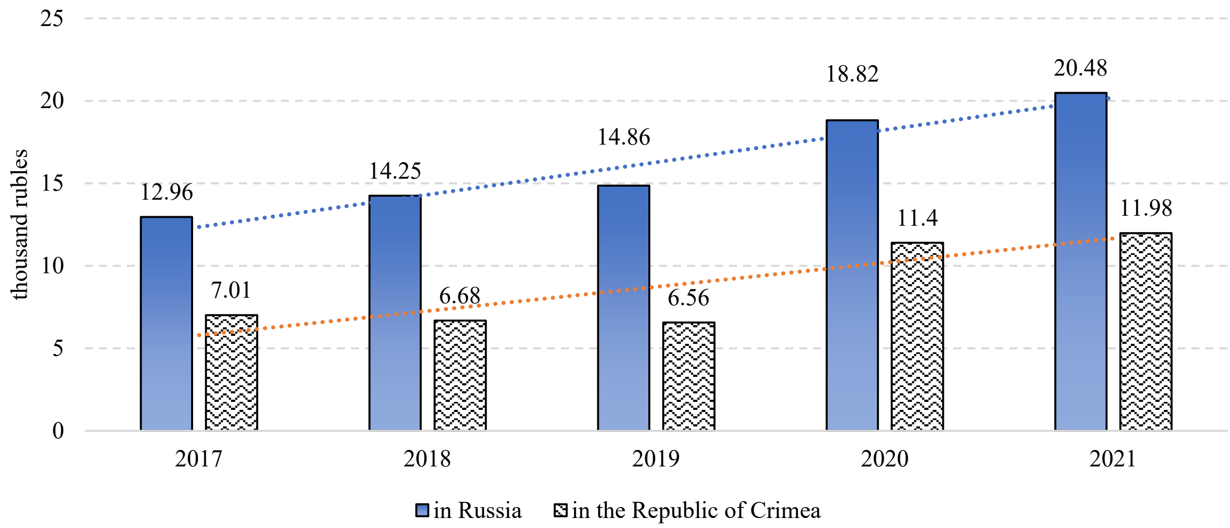


Fig. 4. Dynamics of the volume of financing for occupational safety measures per employee from 2017 to 2021, thousand rubles

As it can be seen from Figure 4, occupational safety costs in Crimea increased by 70%, from 7 thousand rubles per employee in 2017 to 12 thousand rubles in 2021. In general, an increase of 58% was recorded in Russia, from 13 thousand rubles to 20.5 thousand rubles.

It is easy to see that the amount of funds allocated to occupational safety in Crimea in 2021 was about 1.7 times lower than the national average. The highest values of fatal injuries in Crimea were recorded in 2018 and 2019. In the same years, the difference between the regional and Russian levels of financing for occupational safety measures was maximum. In Crimea, 2.2 times less was spent per employee than the national average. One possible explanation was the lack of resources to provide occupational safety.

Relative OI indicators (per 1 000 employees) in the region were noticeably lower than the average for the Russian Federation. So, in 2021, per 1,000 employees, the number of injured in the industries of the Republic of Crimea turned out to be 36% lower, and the number of fatalities was 20% lower (Fig. 3). However, we believe that this was not due to the effectiveness of occupational safety measures, but rather to the regional structure of industrial injuries by type of economic activity. The low number of victims was generally characteristic of the Southern Federal District. This is due to the lower number of people employed in industry, mining, and manufacturing enterprises. A significant part of the population of the southern regions worked in the service sector.

Discussion and Conclusion. In the period from 2017 to 2021, funding for occupational safety measures at enterprises in Crimea and Russia as a whole increased. At the same time, the rates of fatal OI increased, and in Crimea this trend was more pronounced than the national average. Apparently, the field of management needs more advanced methods for evaluating the effectiveness of measures. In the annual ranking of the subjects of the Russian Federation in terms of compliance with labor legislation[5] the Republic of Crimea moved from the third place in 2017 to the 42nd place in 2018. In 2019, the region took the 20th place. The list was compiled by the Federal Ministry of Labor. It also ranked the activities of the relevant regional executive authorities. According to the results of 2021, Crimea was ranked 60th out of 85 subjects of the Russian Federation in this list.

It is certainly necessary to thoroughly study and analyze the issues of OI prevention at construction sites in Crimea. This is evidenced by the almost twofold excess of the number of victims of accidents in the construction industry in the Republic of Crimea compared to the national average.

The highest number of fatalities is recorded in the construction and agricultural sectors of the republic. Therefore, these sectors require more effective environmental protection measures, improved methods for preventing workplace accidents, and adequate indicators to assess the dynamics of occupational safety and health [11].

In general, the results of the presented work indicate positive changes in ensuring industrial safety in the Republic of Crimea. This opens up prospects for further research and the application of the data obtained. The data can be used to develop indicators of industrial safety, tools for forecasting and analyzing occupational safety at the regional and national levels. An interdisciplinary approach to the problem of occupational injuries opens up prospects for the promotion of new methods for preventing accidents at work.

[5] *Rating of Executive Authorities on Labor of the Subjects of the Russian Federation on the Implementation of State Management of Labor Protection.* Ministry of Labor of Russia. URL: https://eisot.rosmintrud.ru/formirovanie-rejtinga-sub-ektov-rossijskoj-federatsii-po-urovnyu-soblyudeniya-trudovogo-zakonodatelstva-i-bazy-obraztsov-luchshej-praktiki1 (accessed: 24.12.2023). (In Russ.).

One of the ways to improve the prevention of occupational injuries in the region is through the development of continuous education in the field of occupational safety. This includes training and retraining of specialists in secondary vocational and higher educational institutions [12]. The information collected on injury rates in different sectors of the regional economy could be incorporated into training programs in subjects such as "Life Safety" and "Occupational Safety".

Current dynamics are partly related to the integration of Crimea after 2014. Indicators are given in comparison with the national ones. It is logical to assume that the results of this scientific work can be used more widely when forming a strategy for the development of occupational safety in new regions of the Russian Federation.

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Research Article

Assessment of the Allergenic Potential of Urban Woody Flora of Rostov-on-Don

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Abstract

Introduction. Plant pollen causes various allergic reactions in humans, including respiratory diseases, immune system disorders, bronchitis, conjunctivitis, dermatitis, and hay fever. These diseases affect up to 30% of the world's population. In large cities, trees and shrubs used in landscaping are significant sources of allergenic dust. Despite this, the greening of cities worldwide often occurs without considering the allergenic properties of plants. With the development of proteomics, it has become possible to assess the degree of allergenicity of proteins that make up plant pollen in detail. Based on this information, a scale of potential allergenicity for woody plants has been developed. The aim of this study is to assess the allergenic potential of woody plants in the urban flora of Rostov-on-Don.

Materials and Methods. The object of the study was trees and shrubs used in the landscaping of Rostov-on-Don. The analysis of floristic data was based on the materials obtained during field work in 2023 on the territory of Rostov-on-Don. The author also used the lists of the city's dendroflora compiled between 2007 and 2022. The assessment of the potential allergenicity of woody plant species was conducted on a five-point scale, with 0 indicating plants that did not pose an allergic hazard, 1 indicating a low allergenicity level, 2 indicating a medium class, 3 indicating a high level, and 4 indicating a very high level of allergenicity.

Results. In the flora of woody plants in Rostov-on-Don, 61 species of potentially allergenic plants were identified, posing varying levels of danger to human health. The share of all types of potentially allergenic woody plants was 30% of the total number of urban woody flora species in the city. The most powerful sources of allergenic pollen included nine species (*Fraxinus Excelsior, Betula Pendula, B. Verrucosa, Platycladus Orientalis,* etc.), which posed the greatest threat of hay fever and other allergic reactions. As a rule, these were typically wind-pollinated plants that produced maximum amounts of pollen. The list of potentially allergenic species included a significant number of adventitious species (24 species), which made it difficult to control their spread. A taxonomic analysis of potentially allergenic species was carried out at the order level, for which specific protein reactions were identified and detailed approaches to the prevention and treatment of hay fever were developed. The orders Pinales and Fagales form the bulk of allergenic pollen in the winter-spring period.

Discussion and Conclusion. For the first time, studies were conducted on the allergenic activity of urban woody flora in the southern regions of Russia. An assessment of their allergenic potential allowed us to determine the level of threat of allergic reactions in humans. The greatest danger comes from both allergenic and invasive species that can spread actively and increase in numbers. Representatives of the Pinales and Fagales orders have proven to be significant sources of allergenic pollen, as they often have high ornamental qualities and play a prominent role in design projects. In some cases, it may be possible to replace these cultures with less allergenic alternatives, such as representatives of the Rosales order, to reduce the risk of allergic reactions.

Keywords: pollen of woody plants, allergies to pollen, urban flora, flora of Rostov-on-Don, adventive species

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Научная статья

Оценка аллергенного потенциала древесной урбанофлоры города Ростова-на-Дону

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Аннотация

Введение. Пыльца растений вызывает у человека разнообразные аллергические реакции, в том числе респираторные заболевания, нарушения иммунной системы, бронхит, конъюнктивит, дерматит, сенную лихорадку. Ими страдает до 30 % населения мира. В крупных городах мощными источниками аллергенной пыльцы являются деревья и кустарники, используемые в зеленом строительстве. Тем не менее, озеленение большинства городов в мире проводится без учета аллергенности применяемых культур. С развитием протеомики появилась возможность детально оценить степень аллергенности различных белков, входящих в состав пыльцы. На этих сведениях сформированы шкалы потенциальной аллергенности древесных растений. Целью данного исследования явилась оценка аллергенного потенциала древесных растений урбанофлоры города Ростова-на-Дону.

Материалы и методы. Объектом исследования послужили деревья и кустарники, используемые в озеленении донской столицы. Анализ флористических данных основан на материалах, полученных в ходе полевых работ в 2023 году на территории города. Также автором использовались списки дедрофлоры города, составленные в период с 2007 по 2022 год. Оценка потенциальной аллергенности видов древесных растений проводилась по пятибалльной шкале, где 0 — растения, не представляющие аллергенной опасности; 1 — низкий класс аллергенности; 2 — средний класс; 3 — высокий класс; 4 — очень высокий класс аллергенности.

Результаты исследования. В составе флоры древесных растений Ростова-на-Дону выявлен 61 вид растений, представляющих разные уровни аллергенной опасности для здоровья человека. Доля исследуемых видов составляет 30 % от общего числа древесной урбанофлоры города. Самыми мощными источниками аллергенной пыльцы являются девять видов (*Fraxinus Excelsior*, *Betula Pendula, B. Verrucosa*, *Platycladus Orientalis* и др.), они представляют наибольшую угрозу возникновения поллинозов и других аллергических реакций. Как правило, это ветроопыляемые растения, продуцирующие максимальное количество пыльцы. Среди потенциально аллергенных видов отмечается значительное количество адвентивных видов (24 вида), что затрудняет контроль над их распространением. Проведен таксономический анализ потенциально аллергенных видов растений на уровне порядков, для которых выявлены специфические реакции белков и разработаны детальные подходы к профилактике и лечению поллинозов. Порядки Pinales и Fagales формируют основную массу аллергенной пыльцы в зимне-весенний период.

Обсуждение и заключение. Исследования аллергенной активности древесной урбанофлоры на юге России проведены впервые. Оценка ее аллергенного потенциала позволила определить степень угрозы возникновения аллергических реакций у людей. Наибольшую опасность представляют одновременно аллергенные и инвазионные виды, способные к активному распространению и увеличению своей численности. Мощными источниками аллергенной пыльцы оказались представители порядков Pinales и Fagales. Они же, как правило, обладают высокими декоративными качествами и играют ведущую роль в дизайнерских проектах. В ряде случаев эти культуры можно замещать менее аллергенными, например, представителями порядка Rosales.

Ключевые слова: пыльца древесных растений, аллергия на пыльцу растений, урбанофлора, флора города Ростова-на-Дону, адвентивные виды

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Introduction. Respiratory diseases associated with atmospheric plant pollen are currently a global public health problem, as they affect about 30% of the world's population [1]. In Russia, allergic rhinitis, as the most common allergic disease, affects from 11 to 24% of the population, depending on the region [2, 3]. Allergic reactions can affect the human immune system and disrupt its work [4]. Pollen allergy can also cause a number of other diseases (bronchitis, conjunctivitis, dermatitis, hay fever). Prolonged exposure to its high concentrations can lead to chronic bronchitis and bronchial asthma [5].

Quite often, pollen allergy is associated only with the flowering of ambrosia (*Ambrosia sp.*) and some types of cereal plants (oats, wheat, corn). However, there are many more sources of allergenic pollen. It is necessary to add to this list cultivated plants (sugar beet, clover, sorrel, sunflower), weeds (dandelion, plantain, nettle, sagebrush, orach) and various types of woody plants. Pollen containing simple alkaloids, amines, saponins, and essential oils most often causes various grass pollen allergies [6]. There is disagreement among scientists about the allergenicity of pollen from coniferous plants such as cypress, yew and pine. Some authors [7] are of the opinion that pollen of coniferous plants has the least pronounced allergenic properties. Other experts [8] note that coniferous species have very high allergenic activity. It is obvious that the landscape and the nature of vegetation play a crucial role in the set of allergenic factors. Undoubtedly, in the conditions of large cities, the allergenic situation will be formed mainly due to woody plants.

There are few studies of urban vegetation as a source of allergens [9, 10]. In some countries of the world, there are aerobic stations that collect data on the content of allergens in the atmosphere. This allows a systematic approach to the study of the problem of identifying allergenic species and determining their level of danger.

One of the first initiatives in the field of determining the allergenicity of garden plant species is the study of T. Ogren [11], who developed the Ogren Plant Allergy Scale (OPALs), a system for measuring the ability of a plant to cause allergic reactions in humans. K. Hruska [12] established the phytoallergenic potential of various plant species present in urban ecosystems of Italy, based on their biological and phenological characteristics. More recent projects are [8, 13] with lists of characteristics and signs of allergenicity of the 100 most used types of urban landscaping. They were compiled in order to identify allergenicity problems in the population. Based on the above-mentioned works, as well as with the involvement of molecular studies of protein compounds in pollen [14], a list of 150 common trees and shrubs of Mediterranean cities was developed with an assessment of their potential allergenicity on a scale from 0 to 4 (VPA).

With the development of molecular biology, in particular proteomics, it was possible to approach the molecular mechanisms of human allergic reactions to pollen particles [15]. It has been established that the most powerful sources of allergens were representatives of the orders Fagales, Lamiales, Proteales and Pinales. The aim of the study presented today is to characterize the allergenicity of woody plants that make up the urban flora of Rostov-on-Don.

Materials and Methods. The object of the study was trees and shrubs that were in a stable and continuous urban landscaping culture. The analysis of floral data was based on materials obtained during field work in 2023 in the city. In addition, during the assessment of urban flora, the authors used the works of Ogorodnikova T.K., Pokhilko L.O., Fedorinova O.I. [16], Kozlovskii B.L., Kuropyatnikov M.V. [17], Berezin V.V. [18]. Invasiveness of plant species was determined in accordance with the data collected by Vinogradova Yu.K., Maiorov S.R., Khorun L.V. [19]. The assessment of the potential allergenicity of woody plant species was carried out on a scale [14], where 0 indicated that the plants did not present an allergenic risk, 1 represented a low allergenic class, 2 was a medium allergenic class, 3 was a high allergenic class, and 4 was a very high allergenic class.

Rostov-on-Don is located in a temperate continental climate zone with mild winters and hot, dry summers. The average air temperature, according to long-term observations, is +11.0°C. The coldest month is January (with an average temperature of –2.0°C). The warmest month is July (with an average temperature of +23.4°C). The average annual precipitation in Rostov-on-Don is 618 mm. The zonal type of vegetation surrounding the urban landscape are steppes [20].

Results. 61 species of potentially allergenic plants representing different levels of danger to human health have been identified in the flora of woody plants of Rostov-on-Don. According to [17], the so-called real assortment of woody plants in the city included 200 species of gymnosperms and angiosperms belonging to 97 genera from 43 families. The species that were in a stable and continuous urban gardening culture were taken into account. Thus, the proportion of all potentially allergenic woody plant species (VPA species) was 30% of the total urban woody flora (Table 1).

Table 1

Potentially allergenic species of woody plants in the urban flora of Rostov-on-Don

Genus (species)	Number of species in the genus	Adventitious	Invasive	VPA	Order
Acer (except *A. negundo*)	4	2		2	Sapindales
Acer negundo		North America	Transformers	2+	Sapindales
Aesculus hippocastanum		Central Europe		1	Sapindales
Ailanthus altissima		Asia	Transformers	3	Sapindales
Betula	2			4	Fagales
Campsis radicans		North America		1	Lamiales
Catalpa bignonioides		North America		1	Lamiales
Cercis siliquastrum		Asia		1	Fabales
Corylus avellana				4	Fagales
Cotoneaster	3			1	Rosales
Crataegus (except *C. monogyna*)	4			1	Rosales
Crataegus monogyna			Invasive plants		Rosales
Elaeagnus angustifolia			Naturalized plants	1	Rosales
Fraxinus excelsior				4	Lamiales
Ginkgo biloba		China		3	*Ginkgoales*
Gleditsia triacanthos		North America		1	Fabales
Hibiscus syriacus		Asia		1	Malvales
Juglans nigra		North America		3	Fagales
Juniperus	2	1		4	Pinales
Ligustrum vulgare				2	Pinales
Malus domestica				1	Rosales
Morus alba		Asia		3	Rosales

Morus nigra		Asia		4	Rosales
Paulownia tomentosa		China		1	Lamiales
Picea pungens		North America		1	Pinales
Pinus sylvestris				2	Pinales
Platanus x acerifolia		Asia		3	Proteales
Platycladus orientalis		China		4	Pinales
Populus alba			Transformers	3	Malpighiales
Populus deltoides				1	Malpighiales
Prunus	2			1	Rosales
Pseudotsuga menziesii		North America		1	Pinales
Pyrus comminis				1	Rosales
Quercus robur				2	Fagales
Rhus typhina		Africa		1	Sapindales
Robinia pseudoacacia		North America		1	Fabales
Rosa canina				1	Rosales
Salix alba				3	Malpighiales
Sambucus nigra				1	Dipsacales
Sophora japonica		Asia		1	Fabales
Sorbus aucuparia				1	Rosales
Spiraea x vanhouttei				1	Rosales
Tamarix tetrandra				2	Caryophyllales
Thuja occidentalis		North America		4	Pinales
Tilia cordata				2	Malvales
Ulmus	3			3	Rosales
Viburnum lantana				1	Dipsacales

It should be noted that the list of VPA species was rather heterogeneous in terms of allergenicity (Fig. 1).

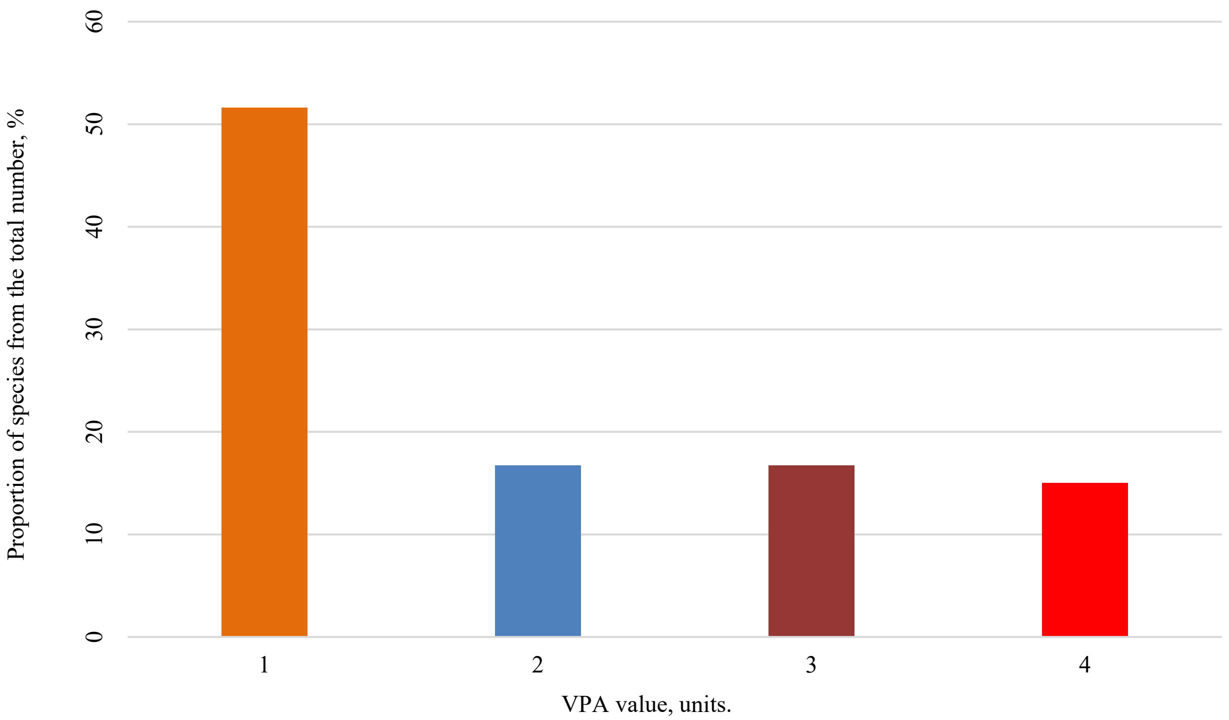

Fig. 1. Distribution of VPA species of urban woody flora of Rostov-on-Don by allergenicity levels

Group No. 1 turned out to be the most numerous, with 31 species, which was 51.6% of the total number of VPA species. They carried a minimal risk of allergic reactions. Nevertheless, this group included quite common breeds in the city, such as *Aesculus hippocastanum, Catalpa bignonioides, Gledicia triacanthos, Robinia pseudoacacia,* etc. These species were entomophilic and produced significantly less pollen than wind-pollinated plants. In some species of this group, only pollen showed allergenic activity, other parts of the plant might have the opposite effect. According to the authors [21], extracts of the fruits of *Gleditsia triacanthos* exhibited pronounced anti-allergenic properties.

Ten species (16.7%) were assigned to the second class of allergenicity. In particular, these were *Acer, Tilia cordata, Pinus sylvestris,* etc. By the nature of pollination, these were mixed species, i.e. insects were used to transfer pollen, but small portions of pollen entered the air in an anemophilic way to attract them [14].

The third category also included ten species (16.7%), which were characterized by a high degree of allergenicity. Among them were *Ulmus, Morus alba, Populus alba, Ailanthus altissima,* etc. When determining the allergenicity of *Ailanthus altissima*, experts could not come to a consensus, since the strategy of its pollination has not yet been clarified, namely whether it is pollinated amphiphilically or anemophilically. In the latter case, there was every reason to place it in the third category of VPA species.

The fourth category included nine species (15%) that posed the greatest potential threat of the occurrence of pollinosis and other allergic reactions. Among them *Fraxinus excelsior, Betula pendula, B. verrucosa, Platycladus orientalis* were well known and widespread, i.e. typically wind-pollinated plants, therefore producing maximum amounts of pollen.

The analysis of the identified potentially allergenic species showed a fairly high percentage of adventitious (alien to local communities) species. It was obvious that pollen from such plants caused more acute and less predictable reactions of the human body, and this happened for at least two reasons. Firstly, it was the lack of immune mechanisms to combat new proteins in the pollen of foreign plants [15], and secondly, some adventitious species aggressively captured new habitats, which led to a sharp increase in their numbers and, consequently, to an increase in pollen mass in the atmosphere. Thus, the proportion of adventitious species in the list of VPA species might carry additional information about the potential allergenic danger of urban flora (Table 1). 24 adventitious potentially allergenic species were found in the urban flora of Rostov-on-Don, which was 12% of their total number. Almost half of these species (45.8%) were from North America, the rest were from Asia or Africa. In addition, allergenic species included five invasive species with different invasive statuses. These species could be introduced into natural cenosises and transform natural ecosystems. It was necessary to control the spread of these species by urban flora monitoring.

Taxonomic analysis of VPA species showed the distribution of potentially allergenic species in orders for which specific protein reactions were identified and detailed approaches to the prevention and treatment of pollinosis were developed (Fig. 2).

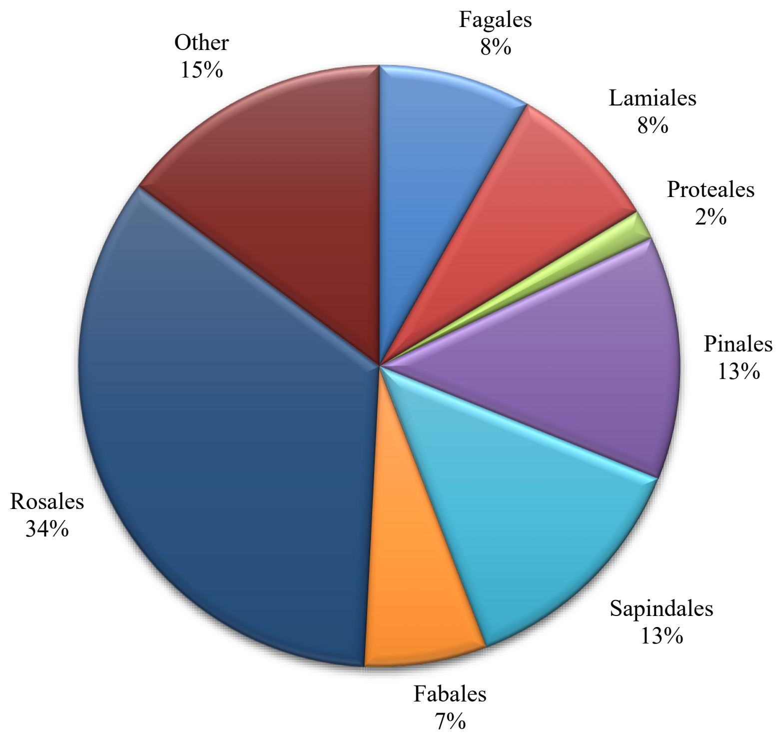

Fig. 2. Distribution of VPA species of urban woody flora of Rostov-on-Don in taxa at the level of orders

Pinales (13.1%) and Sapindales (13.1%) were the leaders in the spectrum of orders. The Pinales order included *Juniperus virginiana, J. sabina* widespread in green construction, which, according to the VPA scale, belonged to a class with a very high content of allergens. According to [22], the allergens Cry j 1 and Cup a 1, which belonged to the family of pectatliase proteins and demonstrated high levels of cross-reactivity, were found in juniper pollen. Pectatliase allergens were identified as major allergens not only in the pollen of Cupressaceae trees, but also in Asteraceae weeds, which brought them closer to ambrosia from this point of view.

The second place in the number of species was shared by the orders Lamiales (8.2%) and Fagales (8.2%). Pollen from Fagales trees was the main cause of winter-spring pollinosis in the temperate climatic zone of the Northern Hemisphere [23]. The order included the families Betulaceae, Juglandaceae, and Fagaceae, which most often caused allergies. A recent study has revealed the similarity of proteins in birch pollen with proteins of the lipocalin family, to which most allergens of animal origin belonged.

In the Lamiales order, only the Oleaceae family included species with allergenic activity. Thus, *Fraxinus excelsior* was a fairly powerful source of allergens. Its pollen productivity could reach the same level as that of birch, while the flowering seasons of both trees overlaped significantly. *Syringa vulgaris* and *Ligustrum vulgare* were two representatives of the Oleaceae family that caused allergies and asthma. Both plants were widely introduced into the culture of green spaces in Rostov-on-Don. Interestingly, *Ligustrum vulgare* was a tree pollinated by insects, so the concentrations of its pollen in the environment were usually very low. Nevertheless, there was evidence that *Ligustrum vulgare* could act as a sensibilizer for allergies to all Lamiales [24].

The Proteales order included only one species, *Platanus x acerifolia*. Platanus was a common species in southern cities, including Rostov-on-Don. The breed had high pollen productivity. For example, in Spain, during the flowering season, the released pollen could reach a level of 14% of the total amount of pollen [25, 26].

The Rosales order included 21 species (34.4%) of woody potentially allergenic plants from the families Rosaceae, Moraceae, Ulmaceae, etc. In this series, the most powerful sources of allergens were representatives of the Moraceae and Ulmaceae, and these were plants with either a mixed type of pollination, such as mulberry, or exclusively anemophilic — elm.

In the other orders, which accounted for 14.8%, only the Malpighiales deserved attention, which included *Populus* and *Salix*. These cultures had moderate allergenic activity.

Discussion and Conclusion. The assessment of the allergenic potential of woody plants of urban flora of Rostov-on-Don allowed us to establish the degree of threat of allergic phenomena among citizens. Determining the level of allergenic activity of each type of arboreal urban flora opens up new opportunities for further design of landscaping facilities that exert minimal stress on the respiratory organs and the human immune system. The greatest danger is posed by both allergenic and invasive species capable of active distribution and an increase in their numbers. The use of such species in the landscape design of the city, as well as the introduction of new similar species in landscaping should be under the control of arborists. The most powerful sources of allergenic pollen were representatives of the Pinales and Fagales orders. They, as a rule, have high decorative qualities and play a leading role in design projects. In some cases, these cultures can be replaced with less allergenic ones, for example, representatives of the Rosales order.

In the future, it is necessary to develop clear recommendations for urban landscape architects to limit the spread of allergenic tree species.

The study of the allergenic activity of arboreal urban flora for the cities of southern Russia was conducted for the first time. Further research will be related to the arboreal urban flora of cities in neighboring regions in order to conduct a comparative analysis.

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ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

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Research Article

EDN: TBZMOY

Dehydration and Environmentally Friendly Thermal Processing of Excess Activated Sludge

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Abstract

Introduction. Currently, there is a problem with the accumulation of large amounts of production waste. One type of this waste is excess activated sludge, which is a waste product from biological wastewater treatment that has a high moisture content. When excess activated sludge is deposited in beds, problems can arise related to changes in the gas-air environment, the release of unpleasant odors, as well as the contamination of groundwater and soil. Prolonged presence of sediment in sludge beds in oxygen-free conditions leads to its decay and deterioration of moisture-yielding properties. For these reasons, the development of new methods for disposing of large volumes of waste generated during wastewater treatment is essential. The aim of this research is to develop a technique for preliminary neutralization and thermal treatment of excess activated sludge using energy waste.

Materials and Methods. The work used excess activated sludge with a moisture content of 98.2% (waste of hazard class IV). Water treatment sludge (waste of hazard class V) was used as a reagent to increase moisture yield. For experimental studies on dehydration, a laboratory centrifuge Elmi CM-6M.01 was used. Tests were conducted under various conditions (500, 1,000, and 1,500 revolutions per second for 1, 2, and 3 minutes), and the value of centrifugation was determined as a criterion for moisture yield in the sludge. Fuel pellets were produced by rolling with technical lignosulfonate as a binding agent. Elemental analysis of the samples was conducted to study the possibility of thermal treatment using an EA 3,000 Euro Vector Analyzer.

Results. A comprehensive technology has been developed to clean the resulting gas emissions from solid particles formed during the combustion of fuel pellets and remove them from the furnace in the form of fly ash along with the outgoing gases. This technology also removed sulfur oxides, nitrogen oxides, and polychlorinated dibenzodioxins and dibenzofurans, while beneficially utilizing flue gas heat by reducing its temperature from 900–1,200°C to 140°C.

Discussion and Conclusion. The approach proposed in this article for the processing and disposal of large volumes of waste allows for the reduction of moisture content of excess activated sludge and the use of this waste as a secondary energy source. This method is environmentally friendly and addresses both technical and environmental challenges, such as the effective recycling of industrial waste and reducing the anthropogenic impact on soil, air, and groundwater. It also provides an opportunity to generate additional electrical and thermal energy through thermal utilization of waste. The results of this work indicate that it is possible to integrate the use of various types of industrial waste (sewage sludge, water treatment waste, and pulp and paper industry waste) as secondary energy sources. These findings have practical implications for enterprises in both the municipal and industrial sectors with wastewater treatment facilities.

Keywords: waste, excess activated sludge, neutralization, thermal disposal, fuel pellets, environmentally safe technology

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Научная статья

Обезвоживание и экологически безопасная термическая переработка избыточного активного ила

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Аннотация

Введение. В настоящее время существует проблема накопления многотоннажных отходов производства. Одним из таких отходов является избыточный активный ил — отход биологической очистки сточных вод, характеризующийся высокой влажностью. При депонировании избыточного активного ила на картах возникают проблемы, связанные с изменением газовоздушного фона, выделением неприятных запахов, а также загрязнением грунтовых вод и почв. Продолжительное нахождение осадка на иловых картах в бескислородных условиях приводит к его загниванию, ухудшению влагоотдающих свойств. По этой причине разработка новых подходов к утилизации многотоннажного отхода, образующегося при очистке сточных вод, является актуальной. Целью данного исследования стала разработка способа предварительного обезвреживания и термической переработки избыточного активного ила с применением отхода энергетики.

Материалы и методы. В работе использовали избыточный активный ил с влажностью 98,2 % (отход IV класса опасности). В качестве реагента для повышения влагоотдачи применяли шлам водоподготовки (отход V класса опасности). Для экспериментальных исследований по обезвоживанию использовали лабораторную центрифугу Elmi CM-6M.01, на которой проводили испытания при различных условиях (500, 1 000 и 1 500 об/сек в течение 1, 2, 3 минут) и определяли значение индекса центрифугирования как критерия влагоотдачи осадка. Топливные гранулы были разработаны методом окатывания с применением в качестве связующего технического лигносульфоната. Элементный анализ образцов с целью изучения возможности термической утилизации проводился с применением анализатора EA 3 000 Euro Vector.

Результаты исследования. Разработана комплексная технология очистки образующихся газовых выбросов от твердых частиц, образующихся при сжигании топливных гранул и выносимых из топки в виде золы-уноса с уходящими газами. При этом одновременно также удаляются оксиды серы, азота, полихлорированные дибензодиоксины и дибензофураны при условии полезного использования тепла дымовых газов за счет снижения их температуры с 900–1 200 °С до 140 °С.

Обсуждение и заключение. Предлагаемый в статье подход к переработке и утилизации многотоннажных отходов позволяет снизить влажность избыточного активного ила и использовать отход в качестве вторичного энергетического ресурса. Такой способ является экологически безопасным и позволяет решить двойную технико-экологическую задачу — эффективную переработку отходов производств, снижение антропогенной нагрузки на почвы, воздух, подземные воды, а также получение дополнительной электрической и тепловой энергии путем термической утилизации. Результаты работы свидетельствуют о возможности комплексного использования комбинации отходов различных производств (осадков сточных вод, отходов водоподготовки и целлюлозно-бумажной промышленности) в качестве вторичных энергетических ресурсов. Полученные результаты представляют практический интерес для предприятий коммунального и промышленного сектора, на которых имеются сооружения очистки сточных вод.

Ключевые слова: отходы, избыточный активный ил, обезвреживание, термическая утилизация, топливные гранулы, экологически безопасная технология

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Introduction. Ensuring environmental safety and reducing the environmental impact on the environment by developing and implementing integrated approaches to waste management is a key goal in the field of sustainable development. However, a significant amount of waste is still disposed of due to a lack of efficient waste processing and disposal facilities. The intensive growth in the volume of various categories of waste leads to an increase in the environmental burden on landfills and storage facilities every year. This results in environmental pollution problems due to improper landfill operations and the need for territorial expansion. A significant portion of the waste currently being disposed of could be recycled and reused, significantly reducing the load on landfills and providing a ready-made secondary resource for further use in the production cycle.

One of these wastes is excess activated sludge, a type of sediment formed in the process of biological wastewater treatment, which is diverted to sludge pits for drying in natural conditions. At the same time, about 100 million tons of such sediment are produced in the Russian Federation each year. The storage of excess activated sludge leads to a change in the gas-air background, the spread of unpleasant odors and bacterial contamination of soils.

Another large volume of waste product is sludge from water treatment of thermal power plants (TPP), which is generated in clarifying filters during liming and coagulation processes of natural make-up water. This sludge is discharged as a pulp into sludge reservoirs. During its storage, there is a risk of soil alkalization and increased mineralization of groundwater.

A common problem that is typical of the storage of large volumes of waste is the alienation of agricultural lands and territories, as well as an increase in anthropogenic load on the environment.

To reduce the anthropogenic load, various methods of the disposal of waste are used, including excess activated sludge [1]. For example, activated sludge is processed to obtain an adsorption material for the sorption of oil and petroleum products [2], as well as to extract phosphates and other pollutants from urban wastewater [3]. Another way to recycle activated sludge is its use as an additive to organic mineral fertilizers [4], in construction in the manufacture of concrete mix [5], as well as in the process of anaerobic fermentation to produce biogas and to use the solid phase (cake) as a fertilizer and recultivant [6]. There are works by foreign and modern authors on the use of the energy potential of excess activated sludge. For example, in [7] it is proposed to obtain hydrogen from waste activated sludge using a microbial electrolytic cell in which organic compounds can be used as a substrate. Pyrolysis of activated sludge is another way to use the energy potential and obtain additional energy during thermal decomposition of excess sludge of pre-pyrolysis gas, semi-coke and liquid fraction [8].

The aim of this work was to study and develop a method for preliminary neutralization and thermal processing of excess activated sludge using large-tonnage energy waste.

Materials and Methods. Experimental laboratory studies were conducted using excess activated sludge, which was obtained from biological wastewater treatment. The species composition of the sludge included protozoa, amoebas, rotifers, infusoria, nematodes, and actinomycetes, as well as other microorganisms.

Activated sludge had a flake-like structure that was brown in color and was a heterogeneous system with fine suspensions. Its granulometric composition was determined, with particles less than 1 mm accounting for 98% of the total, particles between 1 and 3 mm accounting for 1.5–1.8%, and particles larger than 3 mm accounting for only 0.4–0.6% of the overall composition. The density of this material was 1.11 g/cm^3. Main organic components of the sludge were proteins, fats, and carbohydrates, which made up 75–85% of its ash-free (organic) matter. The remaining 15–20% was accounted for by a lignin-humus complex [9]. Table 1 shows the component composition of excess activated sludge. Protein substances were mainly present in raw sludge, while humic compounds were present in fermented sludge [10].

Table 1

Component composition of excess sludge

Parameter	Ash content	α-cellulose	Hemicellulose	Proteins, humates	Fats	Total nitrogen	Phosphorus
%	12.00–15.00	0.80–2.00	2.20–2.60	30.00–35.00	7.11–14.00	6.80–7.30	5.40

Humidity of the activated sludge used after secondary settling tanks was 98.2%, after settling under the influence of gravity it decreased to 94%. Ash content of activated sludge was 12.2%. Excess activated sludge belonged to hazard class IV.

Chemical composition of the mineral part of the excess activated sludge included (wt. %): SiO_2 — 35.7; Al_2O_3 — 12.3; Fe_2O_3 — 7.8; CaO — 14.2; MgO — 9.4; K_2O — 0.8; Na_2O — 2.1; ZnO — 0.22; CuO — 0.12; NiO — 0.28; Cr_2O_3 — 0.23.

Excess activated sludge belongs to the group of hygrophilic organic substrates that easily rot and. For this reason, it was treated [11]. The organic part of the excess activated sludge was subject to rapid rotting with the release of an unpleasant odor, while the number of colloidal and fine particles increased, as a result of which sediment moisture yield decreased [12].

Moisture of activated sludge included free, colloid-bound and hygroscopic forms. Free moisture was not associated with solid particles and was easily removed by drying on sludge beds, filtration or extraction at low pressures, and dehydration [13]. Colloid-bound moisture was extracted from sediment with higher energy consumption, could be removed by filtration and centrifugation during coagulation. Complete removal of colloid-bound moisture was possible only by drying at elevated temperatures. Hygroscopic (or chemically bound) moisture made up to 8–10% of the total mass of water and was not removed even during thermal drying, but only by sludge combustion [14].

In addition to high humidity, activated sludge was characterized by low moisture loss, which was due to the presence of colloid-bound and hygroscopic moisture in it. Colloid-bound moisture was present in the activated sludge due to the processes of rotting of its organic part, since rotting was characterized by increased formation of fine, colloidal particles.

In the study, it was proposed to extract colloid-bound moisture by pretreating excess activated sludge with sludge from thermal power plant water treatment and further their joint centrifugation.

It was proposed to use TPP water treatment sludge as a reagent, which was a waste of hazard class V, formed during the preparation of make-up water at TPP. In this case, the slurry pulp was sent to sludge accumulators for its placement and storage. Chemical composition of carbonate sludge of Kazan TPP-1 (% by weight): Ca^{2+} — 87; Mg^{2+} — 9.7; CO_3^{2-} — 71.7; OH^- — 10.03; SO_4^{2-} — 5.7.

During the experimental studies, the moisture content of the slurry pulp was reduced from 87% to 3% by dewatering the waste in the heat drying shop. Humic substances in the amount of up to 11% of the total mass of the sample were present in the sludge, which was determined by gas chromatography-mass spectrometry [15]. The physical-chemical characteristics of the sludge were determined: bulk density — 572 kg/m^3, ash content of the sludge — 89%, moisture capacity — 56% (wt.), pH of the medium — 8.54. Granulometric analysis conducted by the sieve analysis method showed that the main fraction of the sludge (about 96%) was 0.09–0.50 mm.

During dosing, the water treatment sludge was evenly distributed among the large fibers and solid particles present in the excess activated sludge, and the sediments were thoroughly mixed.

In experimental studies, an Elmi SM-6M.01 laboratory centrifuge was used to dewater excess activated sludge. The waste pre-mixed in various proportions (activated sludge and sludge) was separated in a centrifuge at speeds of 500, 1,000 and 1,500 r/s for 1, 2, 3 minutes.

Further, the centrifugation index was determined as a criterion for sludge water yielding capacity [16].

The assessment of moisture yield and sedimentation properties of activated sludge was carried out according to the value of the centrifugation index I (cm^3/g), calculated according to formula:

$$I = \frac{V_k}{V_0 \cdot C},$$

where $V_к$ and V_0 — volume of compacted and initial sediment, cm^3; C — concentration of initial sediment, g/cm^3.

Centrifugation index, as a parameter as a criterion, allowed an assessment of the increase in the efficiency of dry matter retention during the pretreatment of excess activated sludge with water treatment sludge. After dehydration, the sediment was sent for thermal disposal. For the convenience of dosing by the rolling method, fuel pellets of 5–7 mm in size were developed. Technical powdered lignosulfonate and technical corn starch were used as a binder. Lignosulfonate was a powder from light yellow to brown in color, which was a by-product of cooking pulp. Technical corn starch was a homogeneous powdery material from white to light yellow in color and acted as one of the most multifunctional raw materials.

The choice of binders was due to their availability, low cost, low humidity (no more than 8% and 10%, respectively) and high heat of combustion (the lowest heat of combustion was 17.2 and 16.8 MJ/kg, respectively) [17]. The selected binders were explosion- and fire-proof.

Next, general technical characteristics of the obtained granules were determined: humidity, ash content, abrasion resistance, bulk density, as well as the heat of combustion of the granules. The elemental analysis of the samples was carried out using an EA 3,000 EuroVector analyzer. Based on the conducted research, a suitable scheme for gas emissions treatment was selected.

To obtain reliable data, all experimental studies were conducted at least three times.

Results. Experimental studies have shown that activated sludge was characterized by high humidity — 98.2%. For effective dewatering, centrifugation of excess activated sludge and sludge of water treatment was carried out. Figure 1 provides the results of experimental studies.

According to the results of the study, it could be seen that with an increase in the dosed sludge, the centrifugation index decreased. The most optimal choice was centrifugation of excess sludge during pretreatment with sludge in the amount of 0.6 g/dm^3 for 1 minute at a speed of 1,000 r/s.

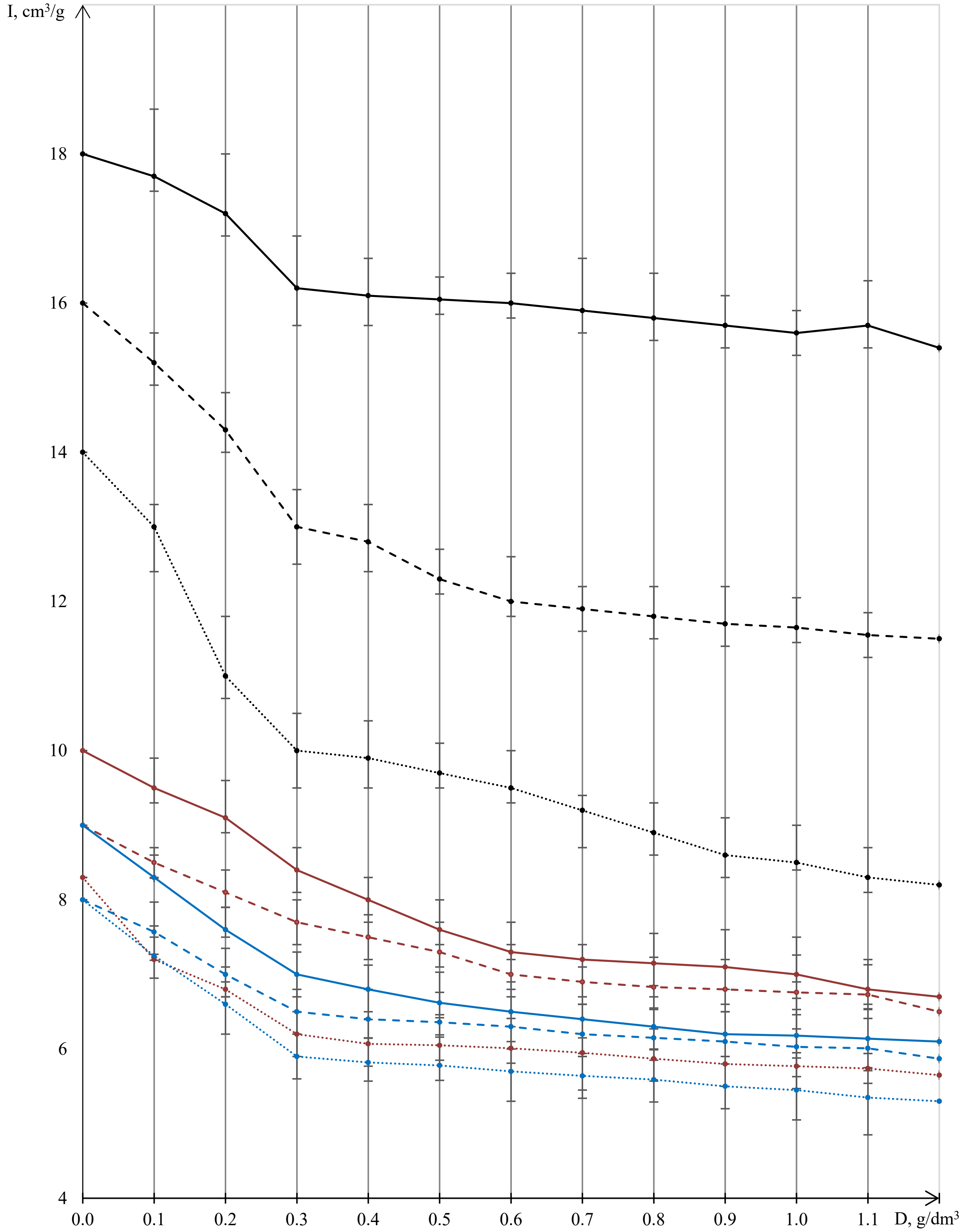

Fig. 1. Dependence of the centrifugation index value (I) on the dose of sludge (D):
— (black) — 500 rpm; — (orange) — 1 000 rpm; — (blue) — 1 500 rpm;
—— — 1 min; ---- — 2 min; -·- — 3 min

During centrifugation, solid particles of water treatment sludge contributed to the rupture of colloidal systems and an increased yield of hydrate-bound moisture. The aggregative stability of excess activated sludge was disrupted, which contributed to increased moisture yield.

In addition, activated sludge particles were an amphoteric colloid and, like most microorganisms, had a negative charge at values of pH=4–9 [18]. The introduction of sludge created pH=8.54, which corresponded to the presented range of values. Activated sludge flakes were negatively charged, since the charge of polymeric substances and microorganisms was close to neutral or slightly negative. In this case, the adsorption of extracellular polymers on microorganisms occurred due to neutral groups and was not associated with a change in charge.

Positively charged Ca^{2+} cations were present on the sludge surface. The extraction of colloid-bound moisture occurred with high efficiency, since when treated with a water treatment sludge acting as a coagulant, charge neutralization and particle enlargement occurred and, as a result, there was an increase in moisture yield properties and a decrease in sediment resistivity.

As a result of pretreatment with sludge and further centrifugation, the structure of the sediment of excess activated sludge changed. Without pretreatment with sludge, the activated sludge firmly retained moisture and was characterized by low moisture yield, while colloid-bound moisture was extracted from the excess activated sludge when the sludge was introduced. As a result, a solid phase was formed, which was easily separated from the centrifuge centrate after centrifugation.

Hygroscopic or chemically bound moisture, which made up about 3–8% of the total moisture present in excess activated sludge, was extracted only during thermal utilization.

Next, the mixed sediment, having a humidity of no more than 60–64%, was sent to the molding of fuel pellets with a diameter of 5–7 mm using binders of technical lignosulfonate and technical starch. Pellets of this size were designed for convenient movement by pneumatic conveying systems, as well as to improve the accuracy of fuel dosing. As binders, preference was given to environmentally friendly substances with good heating value and bonding properties.

Important characteristics of the obtained granules, which affected the efficiency of thermal processing, were the technical and thermal properties, which are presented in Table 2.

According to the research results, the main energy indicator characterizing fuel pellets was the heat of combustion. For this reason, granules with technical lignosulfonate were selected for thermal processing, since they had higher heating value. The resulting value of the heat of combustion of the developed granules was comparable to the heating value of peat.

Table 2

Technical characteristics of fuel pellets

Samples with binders	Industrial starch (22% weight)	Industrial lignosulfonate (22% weight)
Moisture content, %	4.8±0.1	3.1±0.1
Bulk density, kg/m^3	828	788
Ash content, %	29.2	27.9
Ash color	light grey	light brown
Abrasion resistance, %	0.5	0.1
Heat of combustion, MJ/kg	9,672.6	10,345.5

Heat of combustion of fuel pellets, in addition to humidity and ash content (external fuel ballast), was determined by the ratio of the main elements (C, H, N, S) and depended on the content of combustible elements (carbon, hydrogen and sulfur) [13].

Elemental composition of fuel pellets using technical lignosulfonate showed the following values: C^p = 30.1%; H^p = 2.9%; S^p = 1.1%; N^p = 1.24%. The main combustible elements included carbon (34.1 MJ/kg) and hydrogen (120.5 MJ/kg). Sulfur and nitrogen in fuel pellets formed toxic oxides of sulfur and nitrogen, which must be extracted from gas emissions after thermal disposal. At the same time, sulfur had a lower heating value (9.3 MJ/kg), and nitrogen was present in fuel granules in the form of organic compounds and reduced the heating value of the fuel.

The technology of sediment utilization based on preliminary dewatering and their thermal processing in a circulating fluidized bed with heat recovery of waste gases formed after the process of activated sludge burning and exhaust gases cleaning was proposed (Fig. 2).

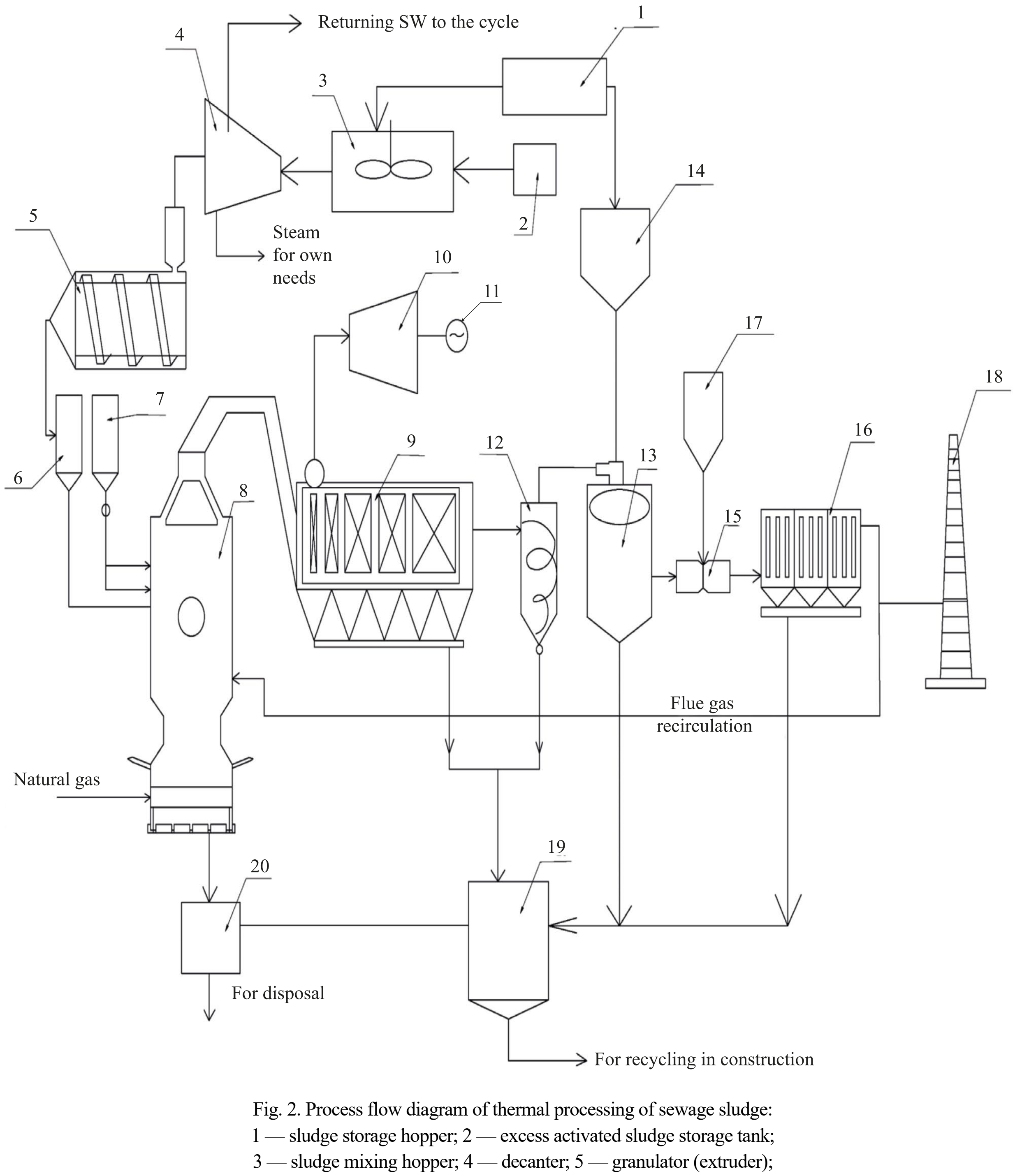

Fig. 2. Process flow diagram of thermal processing of sewage sludge:
1 — sludge storage hopper; 2 — excess activated sludge storage tank;
3 — sludge mixing hopper; 4 — decanter; 5 — granulator (extruder);
6 — fuel pellet storage hopper; 7 — inert material storage hopper; 8 — boiler with circulating fluidized bed;
9 — flue gas heat recovery boiler; 10 — steam turbine;
11 — electric generator; 12 — cyclone; 13 — spraying absorber;
14 — suspended mixture preparation hopper; 15 — activated carbon injection unit;
16 — bag filter; 17 — activated carbon storage hopper; 18 — chimney; 19 — ash and reaction products collection hopper;
20 — slag collection hopper

Combustion of granules from storage hopper 6 took place in boiler with circulating fluidized bed 8, which was characterized by the effect of fluidization or “boiling” due to an ascending gas flow and intensive mixing of particles (with the participation of an inert material from hopper 7 — sand (silicon oxide), which had a high specific heat capacity (0.835 kJ/(kg K)), stabilizing the temperature of the process with qualitative or quantitative fluctuations of fuel pellets based on activated sludge). Intense boiling of the layer contributed to the mixing of fuel granules, oxidizer, and combustion products. Therefore, there was no need for additional mechanical mixing of the granules. Natural gas was supplied for ignition during the start-up of the installation.

After combustion, gases with a temperature of about 900–1,200°C passed through heat recovery boiler 9, in which chemically desalinated water was heated to a vapor state. Steam was directed to turbine 10, and electric energy was generated using electric generator 11. Part of the steam from the heating selections was directed to the enterprise’s own needs. Gases cooled to a temperature of 200-250°C were sent for purification to a filter unit consisting of mechanical cleaning and equipment for cleaning gas emissions by absorption and adsorption methods. Capture of solid dispersed particles was carried out by cyclones and bag filters. Cooled gases entered cyclones 12 to extract fly ash, as well as inert material carried out with flue gases. Next, the flue gases were sent to spraying adsorber 13, in which they were completely refined from hydrogen chloride, sulfur dioxide, nitrogen oxides, as well as partially from polychlorinated dibenzodioxins and dibenzofurans. To do this, the waste of water treatment from hopper 1 was dosed as a sorption material. After spraying adsorber 13, the temperature of the exhaust gases was 140°C. Aftertreatment from polychlorinated dibenzodioxins and dibenzofurans was carried out by spraying activated carbon from hopper 17 in unit 15 in front of the bag filters. The remaining fly ash, as well as unreacted sludge and chemical reaction products, were captured using bag filter 16 and collected in ash and reaction products collection hopper 19. After cleaning the flue gases using bag filters 16, a flue gas recirculation method was used to purify emissions into the atmosphere from nitrogen oxides by taking 20–30% of the gas media from the flue and feeding them into the active combustion zone of boiler with a circulating fluidized bed 8. After complete purification, the exhaust gases were sent to chimney 18.

Discussion and Conclusion. The research results obtained indicate the presence of an energy potential in the developed granules that can be converted into thermal and electric energy while ensuring environmental safety and minimizing negative impacts on the environment.

The choice of a circulating fluidized bed boiler is the optimal solution for this technology compared to other existing options, as the intense boiling in the bed contributes to the mixing of fuel granules, oxidizer, and combustion products, eliminating the need for additional mechanical mixing. Natural gas is used to ignite the granules during start-up.

When using fuel pellets made from activated sludge in a boiler with a fluidized bed, thermal decomposition of calcium carbonate takes place at a temperature of 900–1,200°C and then further binding of sulfur oxide to produce gypsum, followed by its removal. The following reactions occur in the bed:

$$CaCO_3 \rightarrow CaO + CO_2 + 178.8\ \text{kJ/mol};$$
$$CaO + SO_2 + 1/2O_2 \rightarrow CaSO_4 - 500\ \text{kJ/mol}.$$

Chlorine and fluorine compounds are also present in the organic part of the activated sludge. In the fluidized bed, chlorine and fluorine compounds undergo high-temperature decomposition (pyrohydrolysis) with conversion to hydrogen chloride and fluoride, which further interact with calcium oxides by the following reactions:

$$CaO + 2HCl \rightarrow CaCl_2 + H_2O;$$
$$CaO + 2HF \rightarrow CaF_2 + H_2O.$$

However, when using this solution, additional purification of gas emissions generated in a boiler with a circulating fluidized bed is required, namely: extraction of solid particles formed during combustion of fuel pellets and removed from the furnace in the form of fly ash with outgoing gases, as well as removal of residual sulfur oxides, nitrogen, polychlorinated dibenzodioxins and dibenzofurans.

The advantage of the approach proposed in the article is the possibility of neutralizing toxic combustion products that are formed during combustion.

Sulfur oxides, hydrogen chloride and fluoride, as well as polychlorinated dibenzodioxins and dibenzofurans are extracted using a spraying adsorber and adsorption aftertreatment of flue gases with activated carbon. Limestone suspension is traditionally dosed in a spray adsorber for aftertreatment. Since calcium carbonate is one of the main components of the water treatment sludge, its use as a waste reagent of thermal energy is realized. An important condition is good mixing of the suspension droplets with the exhaust gases, as well as ensuring fine spraying of the suspension.

When SO_2 is absorbed by the sludge of thermal power engineering, chemical reactions occur:

$$H_2SO_3 \leftrightarrow SO_2 + H_2O;$$
$$H_2SO_3 + CaCO_3 + H_2O \rightarrow CaSO_3 \cdot H_2O \downarrow + CO_2 \uparrow.$$

The removal of polychlorinated dibenzodioxins and dibenzofurans partially occurs in a spraying adsorber by the following reactions:

$$C_{12}H_nCl_{8-n} \cdot O_2 + (9 + 0.5n)O_2 \rightarrow (n-4)H_2O + 12CO_2 + (8-n)HCl$$
$$C_{12}H_nCl_{8-n} \cdot O + (9.5 + 0.5n)O_2 \rightarrow (n-4)H_2O + 12CO_2 + (8-n)HCl$$

This approach has shown its effectiveness in the incineration of municipal solid waste [19] and can also be implemented in practice of thermal disposal of sewage sludge.

For complete purification of flue gases from nitrogen oxides to the values of permissible emission standards, partial recirculation of flue gases is carried out by supplying them to the active combustion zone of the boiler. This approach makes it possible to reduce the concentration of NO_x to the required values. This method is widely used in the combustion processes of power boilers and can also be used for boilers with a circulating fluidized bed.

The application of the proposed method of thermal neutralization of industrial waste — excess activated sludge and sludge of thermal power engineering — by various industries allows us to preserve natural types of organic fuels and reduces the anthropogenic load on the environment. At the same time, a double technical and environmental task is solved: effective recycling of industrial waste, elimination of sludge pits, sludge collectors and related problems associated with the storage of multi-tonnage waste and alienation of territories, as well as obtaining additional energy using an environmentally safe method of thermal neutralization.

Thus, the proposed approach allows for the implementation of an environmentally friendly method of waste disposal while implementing environmental protection measures. It effectively recycles multi-tonne waste and implements the principle of energy conservation at industrial and municipal facilities that have a wastewater treatment system.

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AI Nurgaliev: experimental studies on characterization, dewatering and development of fuel pellets, scientific article design.

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Research Article

Assessment of Environmental Risks of a Shallow Water Body during Dredging Works

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Abstract
Introduction. The increasing anthropogenic impact on water bodies necessitates integrated solutions to assess environmental risks. Literature describes the stages of risk assessment, the possibilities of environmental management, and expert analysis, while risk modeling in this field is being investigated. However, the potential for predicting risks to water quality and biodiversity during frequently performed hydraulic engineering works such as dredging has not been fully explored. The relevance and practical significance of such an approach are evident. This study aims to develop a mathematical model and software package that can assess risks to species diversity of the ecosystem of a shallow reservoir ecosystem during work in its water area.
Materials and Methods. The starting point for the simulation was a description of the movement of water masses based on the Navier-Stokes equations and the continuity equation at variable density. We used the diffusion-convection equation to predict the transfer of suspended and dissolved particles, as well as to assess the impact of impurities during eutrophication. To create the algorithm, we utilized the terms and definitions defined by the state standard for risk management in emergency situations.
Results. To test the solution, we took data on hydro-mechanical work in the port area of Arkhangelsk. We visualized the concentration fields of suspended particles 0, 15, 30 and 45 minutes after the soil was unloaded. It was found that during the settling of the suspension, the area of its distribution expanded significantly, and this was fully consistent with the data of field experiments during dredging. We calculated and tabulated the volumes of contaminated water at soil dumps in three sites (with a single discharge and in total). To assess the risks to the Sea of Azov, we used the maximum concentrations of pollutant (copper) obtained through measurements, modeling and remote sensing of the Earth. In tests to determine the potential danger of the substance, we assumed that its concentration caused a reaction in 50% of organisms. For fish, the potentially dangerous concentration was 4 mg/l with a duration of 96 hours of exposure. For zooplankton — 50 mg/l and 48 hours. For microalgae, 20 mg/l and 72 hours. The normalized risk value $R_n \approx 0.52$ was obtained. The risk of copper concentration of 80 μg/l in the waters of the Azov Sea was recognized as significant. A tendency towards increasing salinity and stratification of water masses in terms of oxygen content has been identified, consistent with the findings of expeditionary research.
Discussion and Conclusion. The developed approach has allowed us to assess the change in the quality of the waters of the Azov Sea and describe some transformations of the water area. Specifically, we are talking about the distribution of suspended particles and areas of their deposition. These processes can lead to changes in the bottom topography, which in turn can reduce the species diversity of the ecosystem.

Keywords: hydrochemical parameters of the water area, forecasting the spread and deposition of suspended particles, modeling the spread of pollutants, reducing the species diversity of the aquatic ecosystem

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Научная статья

Оценка экологических рисков мелководного водоема при проведении дноуглубительных работ

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Аннотация

Введение. Усиление антропогенного воздействия на водные объекты требует комплексных решений для оценки экологических рисков. В литературе описаны этапы оценки, возможности экологического менеджмента и экспертного анализа. Исследуется моделирование рисков в данной сфере. При этом не изучен потенциал прогнозирования рисков для состояния воды и биоразнообразия в ходе часто выполняемых гидротехнических работ, например дноуглубления. Очевидны актуальность и важное прикладное значение такого подхода. Цель исследования — описание математической модели и программного комплекса, которые позволят оценивать риски для видового разнообразия экосистемы мелководного водоема при проведении работ в акватории.

Материалы и методы. Исходной точкой моделирования было описание процесса движения водных масс по уравнениям Навье — Стокса и неразрывности при переменной плотности. Уравнение диффузии-конвекции использовали для прогнозирования переноса взвешенных и растворенных частиц и оценки влияния примесей при эвтрофикации. Создавая алгоритм, задействовали термины и определения, принятые Росстандартом для управления рисками в чрезвычайной ситуации.

Результаты исследования. Для тестирования решения взяли данные о гидромеханических работах в районе порта Архангельска. Визуализировали поля концентрации взвешенных частиц, через 0, 15, 30 и 45 минут после выгрузки грунта. Установлено, что в процессе оседания взвеси область ее распространения значительно расширяется, и это полностью согласуется с данными натурных экспериментов при проведении дноуглубительных работ. Рассчитали и свели в таблицу объемы загрязненной воды при отвалах грунта на трех участках (при однократном сбросе и в сумме). Для оценки рисков Азовского моря брали максимальные концентрации загрязняющего вещества (меди), полученные в ходе замеров, моделирования и дистанционного зондирования Земли. В тестах для определения потенциальной опасности вещества исходили из того, что его концентрация вызывает реакцию у 50 % организмов. Для рыб потенциально опасная концентрация — 4 мг/л при длительности влияния 96 ч. Для зоопланктона — 50 мг/л и 48 ч. Для микроводорослей 20 мг/л и 72 ч. Получено значение нормализованного риска — $R_n \approx 0{,}52$. Признан значимым риск концентрации меди 80 мкг/л в водах Азовского моря. Выявлена тенденция увеличения солености Азовского моря и стратификация водных масс по содержанию кислорода, что согласуется с результатами экспедиционных исследований.

Обсуждение и заключение. Разработанный подход позволил оценить изменение качества вод Азовского моря и описать некоторые трансформации акватории. Речь идет, в частности, о распространении взвешенных частиц и о районах их оседания. Указанные процессы обусловливают изменение рельефа дна, которое, в свою очередь, может привести к сокращению видового состава водоема.

Ключевые слова: гидрохимические параметры акватории, прогноз распространения и осаждения взвешенных частиц, моделирование распространения загрязняющих веществ, сокращение видового разнообразия водной экосистемы

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Introduction. The development of the economy is accompanied by large-scale works on the territory of water bodies. The examples include the construction of the Golden, Russian and Crimean bridges, dredging in order to expand water areas for navigation, laying underwater gas and oil pipelines, and much more. Fundamental part of such projects is the assessment of potential environmental impacts and risk forecasting. In Russia, these issues are regulated by the Requirements for Environmental Impact Assessment Materials[1]. Additionally, GOST R ISO 14001–2016, which is the official translation of the international standard ISO 14001:2015, is used to define the activities of enterprises and their environmental management systems when forming applications and implementing projects. It is worth noting that the current version of the standard is focused on preventing emergency situations, rather than eliminating their consequences.

The authors of [1] identify three stages of environmental risk assessment, while work [2] describes five stages. Paper [3] focuses on the risks of oil and gas companies. It also discusses positive aspects of the implementation of an environmental management system.

A significant part of the materials is devoted to the development of corporate environmental management systems to ensure international or national security in the field of ecology [4]. In [5], the correlation of the company's environmental responsibility and the value of its shares on the stock market are studied. A similar problem is considered in [6]. The point is that the environmental responsibility of the French company has affected the growth of its market value. The impact on the capitalization of the Green Company Awards was assessed, which recognizes the best facilities and enterprises from the point of view of ecology [7]. In many cases, an expert approach to assessing environmental risks of companies is taken into account [8]. However, it has significant drawbacks related to the subjectivity of conclusions and the complexity of processing a large amount of information in conditions of uncertainty [9]. Therefore, mathematical methods of risk assessment are more preferable.

Paper [10] describes popular approaches to risk assessment with an emphasis on the index approach. In [11], the authors consider a model for assessing environmental risks using the Dempster-Schafer evidence theory, which has proven itself well in solving problems under conditions of uncertainty. Nevertheless, its practical application is complicated by the need for many complex calculations, including combined ones. Article [12] describes a mathematical model based on a probabilistic approach and the determination of the integral value of risk assessment. The literature does not consider the possibility of predicting a set of risks for the state of water and biodiversity when performing hydraulic engineering works. However, it is precisely this approach that should be recognized as relevant, having obvious practical significance at the present stage of economic development.

The aim of the presented study was to describe a mathematical model and a software package that allowed assessing vulnerabilities and risks for the hydrochemical parameters of water area and species diversity of the ecosystem of a reservoir when deepening the bottom of a shallow reservoir. First of all, it concerned forecasting the propagation and deposition of suspended particles. These processes significantly affect the relief of the bottom surface. In addition, zones of distribution of pollutants were modeled. Their toxicity can become a factor in reducing the species diversity of aquatic ecosystems.

Materials and Methods. To predict the results of anthropogenic impact on a reservoir ecosystem (for example, during dredging), a comprehensive mathematical model of suspended particles movement in the water environment was proposed. It took into account wind currents, the movement of the aquatic environment and river flows, water body geometry, turbulent exchange, and variable density of the aquatic environment, which could be influenced by factors such as salinity or suspended matter. The model also considered the deposition rate of each particle fraction, determined by its size and shape. In addition, it could be supplemented by a model for reservoir eutrophication, which would take into account nutrient levels and their impact on processes within the reservoir.

Problem statement

A model of water movement. To describe the movement of water masses in a water body, we used a hydrodynamic model [13]. This model included the following expressions:

1. Navier—Stokes equations of motion:

$$
\begin{gathered}
\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu\frac{\partial u}{\partial z}\right),\\
\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu\frac{\partial v}{\partial z}\right),\\
\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z}+\frac{\partial}{\partial x}\left(\mu\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu\frac{\partial w}{\partial z}\right)+g.
\end{gathered}
\tag{1}
$$

[1] *On approval of requirements for environmental impact assessment materials.* Order of the Ministry of Natural Resources and Ecology of the Russian Federation. URL: https://docs.cntd.ru/document/573339130 (accessed: 26.02.2024). (In Russ.).

Here $V = \{u, v, w\}$ — velocity vector of the water medium [m/s]; P — pressure [Pa]; ρ — density [kg/m^3]; μ, ν — horizontal and vertical components of turbulent exchange coefficient [m^2/s]; g — acceleration of gravity [m/s^2].

2. Continuity equation in the of variable density:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0. \tag{2}$$

The initial and boundary conditions for the system of equations (1) and (2) were described in detail in [13].

A model for suspended particles propagation. To predict the transport of both suspended and dissolved particles, we used a diffusion-convection equation [14]:

$$\frac{\partial c_r}{\partial t} + \frac{\partial (u c_r)}{\partial x} + \frac{\partial (v c_r)}{\partial y} + \frac{\partial \left((w + w_{s,r}) c_r \right)}{\partial z} = \frac{\partial}{\partial x}\left(\mu \frac{\partial c_r}{\partial x} \right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial c_r}{\partial y} \right) + \frac{\partial}{\partial z}\left(\nu \frac{\partial c_r}{\partial z} \right) + F_r, \tag{3}$$

where c_r — concentration of the r-th fraction of suspension [mg/l]; $w_{s,r}$ — rate of gravitational deposition of the r-th fraction of suspension [m/s]; F_r — intensity function of the sources of the r-th fraction of suspension [mg/(l·s)].

System of equations (3) was considered under the initial and boundary conditions described in detail in [14].

Based on system (1)–(3), it was possible to simulate the processes of movement and deposition of suspended particles during dredging, as well as consider the possibility of optimizing the areas of soil dumps. It was advisable to use these models to reduce harm to the ecosystem of a reservoir.

An eutrophication model. To assess the effect of impurities, let us consider a model of eutrophication of waters based on diffusion-convection equation [15]:

$$\frac{\partial S_r}{\partial t} + \frac{\partial (u S_r)}{\partial x} + \frac{\partial (v S_r)}{\partial y} + \frac{\partial \left((w + w_{s,r}) S_r \right)}{\partial z} = \frac{\partial}{\partial x}\left(\mu \frac{\partial S_r}{\partial x} \right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial S_r}{\partial y} \right) + \frac{\partial}{\partial z}\left(\nu \frac{\partial S_r}{\partial z} \right) + F_r, \tag{4}$$

where S_r — concentration of the r-th impurity [mg/l]; $w_{s,r}$ — rate of gravitational deposition of the r-th impurity [m/s]; F_r — function describing the intensity of a chemical-biological source of the r-th impurity [mg/(l·s)].

System of equations (4) was considered under the initial and boundary conditions, which were given in [15].

You can use (4), in particular, to describe:

– the influence of impurities entering the reservoir as a result of anthropogenic impact, for example, in an emergency situation or wastewater discharge;

– processes of oxidation and reduction of manganese;

– oxidation of hydrogen sulfide;

– calculation of the concentration of dissolved oxygen in water.

Data on the location of sources can be obtained using remote sensing of the Earth.

An algorithm for assessing the risk of anthropogenic impact. Known approaches to risk understanding were systematized in [16]. This paper used the definition of risk according to GOST R 55059-2012[2]. Risk is the probability of an emergency or the expected amount of damage associated with the realization of an adverse events. Let us consider an example when impurities enter the water that negatively affects the ecosystem:

$$R = Ef_S \cdot E_S. \tag{5}$$

Here R — risk factor; Ef_S — potential danger or toxicity of the impurity; E_S — exposure factor or the amount of impurity in terms of one biological target. For a reservoir, the exposure factor could be calculated using formula:

$$E_S = S \cdot P_S \cdot k_{BA}, \tag{6}$$

where S — impurity concentration specified or calculated based on model (4); P_S — hydrolysis rate index; k_{BA} — bioaccumulation[3] or accumulation factor (for example, heavy metals) [17].

In world practice, it is customary to use a set of standardized tests[4] to determine the potential danger of an impurity or a contaminant Ef_S. In the European Union countries, quantitative assessments of the toxicity of the substance described below are distinguished.

– *NOEC* — no observed effect concentration, the maximum inactive concentration of the substance. As a rule, this concentration, compared with the control one, does not cause a statistically significant negative effect (the probability of its occurrence does not exceed 0.05) during a given exposure time.

[2] *GOST R 55059–2012. Safety in emergencies. Emergency risk management. Terms and definitions*. Moscow: Standartinform, 2018. 8 P. (In Russ.)

[3] *Methods for Measuring the Toxicity and Bioaccumulation of Sediment-Associated Contaminants with Freshwater Invertebrates*. Second edition. Washington: United States Environmental protection agency; 1994. 148 p.

[4] *Guidance on information requirements and chemical safety assessment. Appendix R10-2 Recommendations for nanomaterials applicable to Chapter R.10 Characterisation of dose [concentration] — response for environment*. European Chemicals Agency. URL: https://echa.europa.eu/guidance-documents/guidance-on-information-requirements-and-chemical-safety-assessment (accessed: 26.02.2024).

– *LOEC* — lowest observed effect concentration. Its action causes a response from the tested organisms. These can be metabolic disorders, as well as disorders of growth, development, reproduction, and even death. *LOEC* values are higher than *NOEC* values. If the effect (percentage of effect) of *LOEC* is known, you can roughly determine *NOEC*: $NOEC = LOEC / 2$ (at $10\% < LOEC < 20\%$). That is, if *LOEC* affects 10–20% of the study population, then the *NOEC* value can be roughly defined as half of *LOEC*.

– *MATC* — maximal acceptable toxicant concentration. This is a calculated parameter defined as the geometric mean of *NOEC* and *LOEC*;

– EC_x — effect concentration (concentration of the effect at which x% of the effect is observed compared to the control group). That is, it is the concentration of a substance at which a response is observed in x% of the tested organisms. For example, at EC_{50} concentration, 50% of organisms react. A statistical method (for example, regression analysis) is often used to calculate this criterion. At the same time, it is necessary to use a sufficient number of concentration groups (doses), since the accuracy of the assessment depends on the number and range of concentrations, and not on the sample size for each concentration. Along with the abbreviation EC_x abbreviations LC_x or $L(E)C_x$ are used.

Within the framework of this study, three sets of tests applicable to natural water bodies were considered.

Results. Based on the considered models and approaches to risk assessment, the five-step algorithm described below was formed.

Step 1. Study of the characteristics of the water area (geographical, climatic, hydrological). This step also meant considering potential sources of suspension and impurities, such as work on the expansion and cleaning of the water area, river runoff, industrial discharges, shipping, etc. It was also necessary to determine the volume of suspended material that could be present.

Step 2. Modeling scenarios for the propagation of suspensions and impurities based on equations (1)–(4).

Step 3. Assessment of toxic effect Ef_S according to three selected tests.

Step 4. Assessment of risk factor for each substance based on (5)–(6) and calculation of normalized risk factor $R_n \in [0, 1]$. For normalization, we used formula $(S - S_{\min})/(S_{\max} - S_{\min})$, where $S_{\min}$ and $S_{\max}$ — minimum and maximum concentrations of the substance in question.

Step 5. Formulation of preliminary conclusions. We considered the risk to be high at $R_n \geq 0.55$, significant at $0.3 \leq R_n \leq 0.55$ and absent at $R_n < 0.3$.

Steps 2–4 can be repeated if you need to determine the best way to carry out the work. For example, during dredging, it was possible to simulate the distribution of suspended solids for various soil discharge points and assess the damage caused to the ecosystem.

A software package in C++ has been developed for the numerical implementation of models (1)–(4) and the above-described risk assessment algorithm for anthropogenic impact. It combined four software modules. The purpose of each of them is described below.

1. Calculation of the three-dimensional velocity vector of the aqueous medium based on the system of equations (1)–(2). Complex geometry of the computational domain was taken into account.

2. Calculation based on the system of equations (3) of the transfer of suspended particles and their settling. In this case, we mean a multicomponent suspension.

3. Modeling of eutrophication of a reservoir based on system of equations (4). Phyto-, zooplankton, as well as 13 chemical elements and their compounds, which significantly affected the hydrobiological processes of the reservoir, were taken into account. These were dissolved oxygen, iron, sulfur, hydrogen sulfide, sulfates, sulfites, nitrogen, ammonium nitrogen, nitrites, nitrates, phosphates, silicates, silicic acid.

4. Assessment of risks of anthropogenic impact based on the algorithm described above.

Modeling of the processes of movement and sedimentation of suspension during soil dumping. The developed software package simulated siltation processes of navigable channels of the Don. In addition, it allowed us to study the transport of suspended particles and the reshaping of the bottom surface in the Azov Sea. Special attention was paid to the coastal and estuarine zones. In addition, the software was used to assess the environmental condition of water areas during dredging operations in the Dvina Bay of the White Sea.

As an example, let us consider modeling the processes of movement and deposition of suspended matter during work on expanding the water area [18]. To this end, we used data on work in the Arkhangelsk port area. To simulate the propagation and deposition of suspended particles, a 3 km long section along the flow direction was taken as the studied area of the reservoir. Its width was 1.4 km, its depth was 10 m.

Physical parameters of the aqueous medium and suspended matter:

– flow velocity — 0.2 m/s;

– suspended matter density — 1,600 kg/m^3;

– suspended matter deposition rate — 2.042 mm/s;

– content of particles with a diameter of less than 0.05 mm in the soil — 26.83%;

– volume of the discharged bulk material — 741 m^3.

Parameters of the calculated area:

– step along horizontal spatial coordinates — 20 m;

– height step — 1 m;

– estimated interval — 2 hours;

– time step — 1 minute.

Figure 1 shows the concentration fields of suspended particles (in mg/l) corresponding to different time intervals. A three-dimensional slice shows a section of the calculated area with a plane that passes through the discharge point and is formed by vectors directed vertically and along the flow (from left to right).

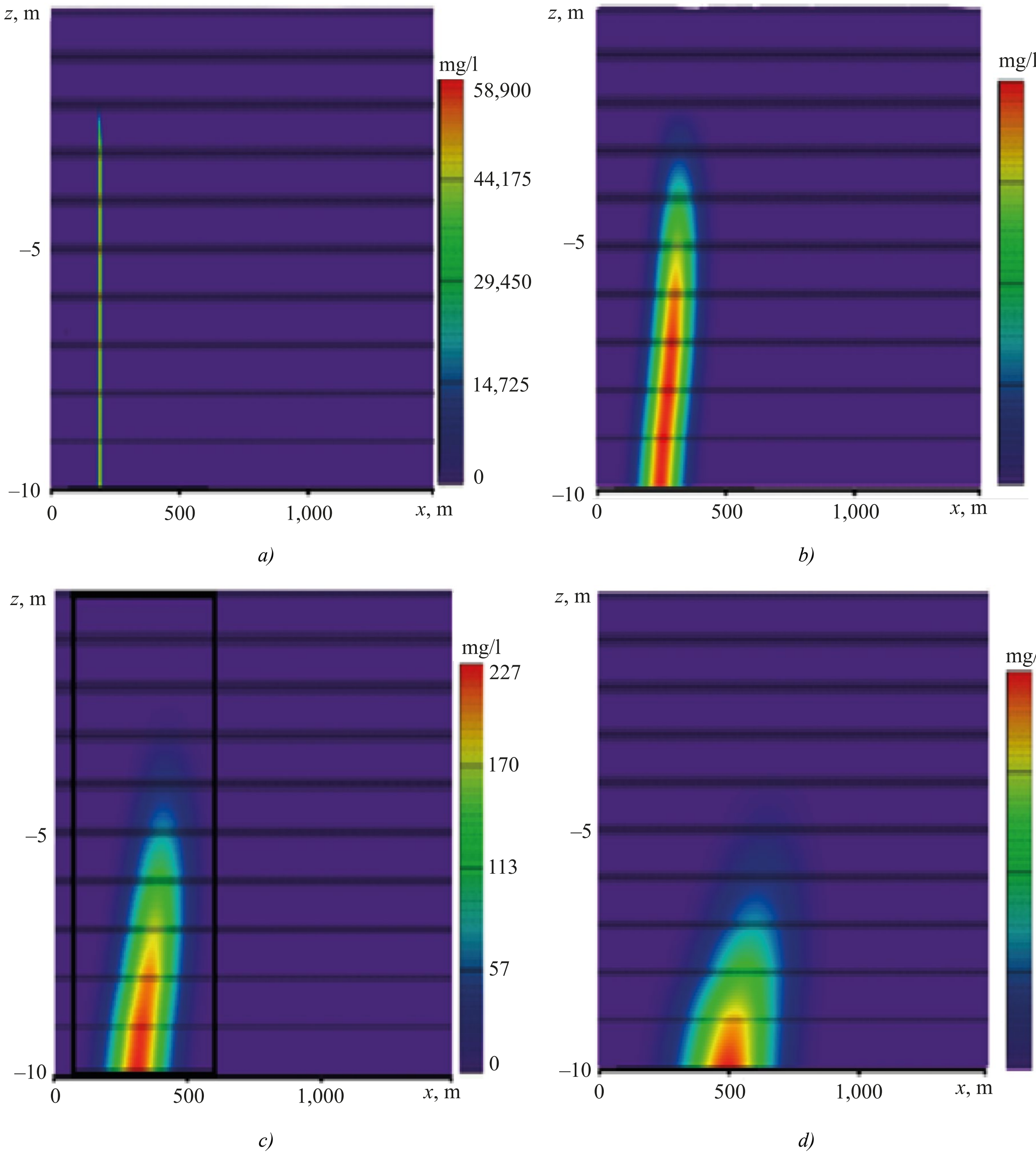

Fig. 1. Fields of concentration of suspended particles (in the "depth — width" section of the reservoir) at different time intervals from the moment of soil unloading: *a* — $T = 0$; *b* — $T = 15$ min; c — $T = 30$ min; *d* — T = 45 min.
The color scale indicates the concentration of the suspension. The horizontal axis represents data on the width of the reservoir, while the vertical axis represents data on depth

Based on the results obtained, the volume of polluted water was calculated at soil dumps at three discharge sites (Table 1).

Table 1

Volumes of polluted water during soil discharge at three sites, million m^3

Site	Volume of polluted water at one discharge, taking into account the concentration of suspended matter in water			Volume of discharges	Total volume of polluted water			
					taking into account the concentration of suspended matter in water			Total
	from 0.25 to 20 mg/l	from 20 to 100 mg/l	more than 100 mg/l		from 0.25 to 20 mg/l	from 20 to 100 mg/l	more than 100 mg/l	
1	0.890	0.245	0.150	124	110.36	30.38	18.6	159.34
2	0.813	0.202	0.105	50	40.65	10.10	5.25	56.00
3	0.889	0.240	0.150	45	40.01	10.80	6.75	57.56

It can be seen from the table that when the soil was discharged, a high concentration of suspension was fixed in a relatively small volume of water (this is, for example, part of the water that was mixed with the soil). A larger amount of water had a lower concentration (such as water in the immediate vicinity of dumped soil). Significant amounts of water were polluted with a lower concentration of suspension during the discharge of soil, its sedimentation and transfer by current.

The areas of soil discharge and the number of discharges were determined according to the terms of reference for work on deepening the port's water area. The areas of the reservoir in which the death of phyto- and zooplankton was possible were identified. The areas of these areas were calculated.

Assessment of the ecological state of the Azov Sea water area. The ecological state of a shallow water body, such as the Azov Sea, was assessed using two different approaches. The first approach involved analyzing databases containing constantly updated data, which were the results of expedition surveys conducted by the authors of this study in the Azov-Black Sea region. The second approach involved the use of software that simulated the hydrodynamics, hydrobiology, and transport of particles in a reservoir. Based on these comparisons, mathematical models were calibrated and validated in order to obtain more accurate risk assessments.

The software package allowed us to assess the risks associated with such phenomena as:

– exceeding the maximum permissible concentrations of dangerous pollutants;

– rapid growth in the process of eutrophication of harmful and toxic algae (also known as "water blooming").

Thus, by using the new software, it was possible to reduce the costs of expeditions for water sampling.

It should also be noted that data from remote sensing of the Earth were used to monitor the ecological state of the studied water body.

Here is an example of how the measurement data from an expedition was processed. Let us take the process of copper discharge from metallurgical plants and its flow into the Azov Sea through the Don River. Copper is a heavy metal that can accumulate in living organisms to dangerous levels.

When assessing the risks associated with a shallow reservoir, such as the Azov Sea, maximum values of pollutant concentrations obtained from measurements, mathematical models, and remote sensing data were used. At a specific point in the reservoir, a measured or calculated concentration value of the pollutant was selected. Let us assume that the measurements revealed an actual concentration of suspended matter in the water to be 80 micrograms per liter. Depending on the location and depth of sampling, copper concentrations in the waters of the Azov Sea ranged from 0.001 to 100 micrograms per liter.

Hydrolysis rate index for copper was assumed to be equal $P_S = 1.5$, bioaccumulation factor (accumulation of matter) — $k_{BA} = 2$. Then according to (6) exposure factor $E_S = 240$ mcg/L.

As noted above, three tests were considered to determine the potential danger of substance Ef_S:

– LC_{50} for 96 hours for fish (sander) — 4 mg/l;

– LC_{50} for 48 hours for zooplankton (daphnia) — 50 mg/l;

– LC_{50} for 72 hours for inhibition of microalgae growth — 20 mg/l.

Let us take into account (5) and the algorithm described above. We get normalized risk value $R_n \approx 0.52$. Thus, the risk of the presence of copper at a concentration of 80 micrograms per liter in the waters of the Azov Sea can be characterized as potentially significant.

It is also worth noting that the model (1)–(4) made it possible to track the trend of increasing salinity of the Azov Sea and the stratification of water masses by oxygen content. This was consistent with the results of earlier expedition studies [19].

Let us focus on the implementation of the 4th step of the algorithm, that is, on the assessment of the risk factor for each pollutant. Using the system (5)–(6), the calculation of normalized risk factor $R_n \in [0, 1]$ and the developed software package, the maximum concentrations of the main pollutants characteristic of the Azov Sea were calculated.

The final risk analysis was carried out based on the results of processing the expedition data and the results of mathematical modeling. Judging by the water pollution index, the ecological condition of the Azov Sea was improving. Previously, water had been defined as "significantly polluted", then as "moderately polluted" [19].

Discussion and Conclusion. The proposed software solution allows us to predict the effects of human activity on the water quality of the Sea of Azov. The developed software package enables us to simulate the movement of suspended particles within the water body, and identify areas where they may settle. These processes can alter the bottom topography, potentially leading to a decrease in species diversity in the areas where sedimentation occurs. Based on the results of our simulations, we can take steps to reduce the area of soil dumped during dredging, thus limiting the damage to the reservoir's ecosystem. By analyzing the data generated by the software, we can assess the potential negative impacts associated with economic losses and risks to human health.

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И.Ю. Кузнецова — разработка программных модулей для расчета процессов движения и оседания взвешенных частиц и оценки параметра риска антропогенного влияния, оформление научной статьи.

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Research Article

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Assessment and Forecasting of Phytosanitary Risks in the Forests of the Irkutsk Region

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Abstract
Introduction. Timber export plays a significant role in the budget of the Irkutsk region. To ensure the continued and sustainable use of forest resources, it is essential to implement preventive measures for forest conservation. One such measure is the analysis of phytosanitary risk, which helps to identify potentially harmful insects and determine the likelihood of their introduction and spread, as well as the potential economic consequences. From the perspective of applied riskology, it is necessary to carry out a predictive assessment, calculate the acceptability of risks and develop methods for managing them, combining economic and monitoring approaches. The aim of the presented work was to assess and predict phytosanitary risks in the Irkutsk region and potential damage to forestry and the economy, as well as to develop measures to reduce them.
Materials and Methods. For this analysis, we used the results of forest surveys conducted in the Irkutsk region in 2021–2023 with the participation of the authors of this article. These surveys included the identification and detection of harmful insects, as well as the determination of their distribution areas according to GOST 34 309–2017 and the methodology approved by the phytosanitary control authority. Additionally, data from official statistics from the Federal Customs Service of Russia for 2021–2023 were used.
Results. We found populations of quarantine pests listed in the Unified List of Quarantine Objects of the Eurasian Economic Union in the forests of Ust-Ilimsky district, such as *Monochamus sutor, Monochamus sartor, Monochamus galloprovincialis, Dendrolimus superans*. We calculated the phytosanitary risk and assessed the quarantine phytosanitary zone, taking into account the buffer zone.
Discussion and Conclusion. The results of the analysis suggest an unfavorable phytosanitary situation in the studied areas. The high infestation of the detected harmful insects in the Ust-Ilimsky district compared to the reference areas indicates the potential for quarantine zones and losses for loggers. To manage phytosanitary risks, it is important to select options that are effective in reducing the spread of quarantine organisms and minimizing risks to an acceptable level. Sanitary logging with timely removal of wind-damaged and fire-affected trees, as well as the use of pheromone traps and biological products, are environmentally friendly options for managing phytosanitary risks.

Keywords: coniferous trees, pests, insects, death, forest diseases, lesions, phytosanitary risk, quarantine zone

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Научная статья

Оценка и прогнозирование фитосанитарных рисков в лесах Иркутской области

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Аннотация

Введение. Экспорт древесины вносит существенный вклад в бюджет Иркутской области, что требует обеспечения сохранения и воспроизводства леса. Одним из важнейших направлений профилактической деятельности по сохранению лесов является анализ фитосанитарного риска. С его помощью устанавливают, являются ли бесконтрольно размножающиеся насекомые вредными, какова вероятность их интродукции, распространения, а также величина экономических последствий. С позиции современной прикладной техносферной рискологии необходимо осуществлять прогнозную оценку, просчитывать приемлемость рисков и разрабатывать методы управления ими, сочетающими экономические и мониторинговые подходы. Целью представленной работы явилась оценка и прогнозирование фитосанитарных рисков на территории Иркутской области и потенциального ущерба лесному хозяйству и экономике, а также разработка мероприятий по их снижению.

Материалы и методы. Для анализа использовали результаты обследований лесных массивов Иркутской области, проведенных в 2021–2023 годах, проведенных с участием авторов данной статьи. Они включали в себя выявление и идентификацию вредоносных насекомых, а также определение площади их распространения по ГОСТ 34309–2017 и методике, согласованной органом фитосанитарного контроля. Помимо этого, использованы данные официальной статистики Федеральной таможенной службы России за 2021–2023 г[1].

Результаты исследования. В лесничествах Усть-Илимского района были обнаружены популяции карантинных вредных организмов, включенные в Единый перечень карантинных объектов Евразийского экономического союза, такие как: малый чёрный еловый усач, большой чёрный еловый усач, чёрный сосновый усач, сибирский шелкопряд. Рассчитан фитосанитарный риск и оценена карантинная фитосанитарная зона с учетом буферной зоны.

Обсуждение и заключение. Результаты проведенного анализа свидетельствуют о неблагоприятной фитосанитарной обстановке на изученных территориях. Выраженная зараженность по выявленным вредным насекомым в Усть-Илимском районе, по сравнению с территориями, взятыми для сравнения, позволяет спрогнозировать карантинные зоны и возможные потери лесозаготовителей. Варианты управления фитосанитарными рисками следует выбирать, исходя из их эффективности в уменьшении скорости распространения карантинных организмов и снижении рисков до приемлемого уровня. Наиболее экологически целесообразным вариантом управления фитосанитарными рисками являются санитарные рубки со своевременной уборкой ветровала и поврежденных пожаром деревьев, установка феромонных ловушек, обработка биопрепаратами.

Ключевые слова: хвойные деревья, вредители, насекомые, гибель, болезни леса, очаги поражения, фитосанитарный риск, карантинная зона

Благодарности. Авторы выражают признательность сотрудникам фитосанитарного контроля и таможенной службы за проявленный интерес к обсуждаемой теме и благодарят редакционную коллегию журнала и рецензента за профессиональный анализ и рекомендации для корректировки статьи.

Для цитирования. Тимофеева С.С., Тенчиков С.В., Тимофеев С.С. Оценка и прогнозирование фитосанитарных рисков в лесах Иркутской области. *Безопасность техногенных и природных систем.* 2024;8(2):47–56. https://doi.org/10.23947/2541-9129-2024-8-2-47-56

Introduction. The condition of forest vegetation in the Irkutsk Region is negatively affected by the presence of needle-eating insects and other harmful pests. Their reproduction can lead to the death and desiccation of trees, causing significant economic losses for forest users. These losses depend on various factors, including species composition of forests, physiological state of trees, the area where the pests are reproducing, their species, population density, and weather conditions. Factors that can negatively impact forests include economically dangerous insects, phytopathogenic viruses and fungi, fires, windfall, droughts, floods, industrial emissions, recreational activities, and others [1].

[1] *Customs statistics. Federal Customs Service.* URL: https://customs.gov.ru/statistic (accessed: 20.02.2024). (In Russ.).

Earlier, the authors have analyzed the environmental risks associated with forest fires in the Baikal region and proposed measures to manage them [2, 3]. They have also addressed the risks of flooding in the region [4]. In addition to fires and floods, significant damage to forests in the region is also caused by the emergence, uncontrolled reproduction, and spread of harmful organisms. It is essential to carry out a quantitative assessment of risks and threats to forest health in these areas, as well as develop and implement measures to manage these phytosanitary risks.

The procedure for analyzing phytosanitary risks, in accordance with international and Russian standards, is the process of determining the level of penetration and spread of harmful organisms in the Russian Federation and related possible consequences [5, 6]. The list of quarantined harmful organisms is determined by federal law, specifically the "On Plant Quarantine" law[2], which came into effect on January 1, 2019. (GOST 34 309-2017[3]).

Regulatory legal acts, including sectoral ones[4], regulate the requirements for the procedure and criteria for assessing phytosanitary risks. These risks are based on a point assessment of the probability of penetration, acclimatization, and the introduction of temporary restrictions on the export of forest products. They also consider potential economic damage and establish ways to manage and prevent such risks, as well as protective measures aimed at monitoring and preventing the spread of harmful organisms. The main goal in identifying harmful organisms is to isolate and destroy them. The list of quarantine organisms includes pests [7], plant pathogens [8], and weed plants [9]. It is important to conduct phytosanitary surveillance at the border during import and export of plant products [10]. Phytosanitary zones, territories where quarantine organisms have been found, should be monitored and timely measures taken to isolate and eliminate them. This is extremely important for the main logging areas of Russia, specifically the Irkutsk Region, where coniferous forests are primarily located and pulp and paper mills that require high-quality raw material are operating. Long-term contracts have been concluded for the export of wood.

A comprehensive assessment of the phytosanitary risks and potential economic losses from exports in the Irkutsk region was conducted previously. Therefore, the aim of this study was to assess and forecast the phytosanitary risks in this region, as well as the potential damage to the forestry industry and the economy. Additionally, measures were developed to reduce these risks.

Materials and Methods. The work is based on materials from surveys conducted by the authors between 2020 and 2023 to identify harmful insects in forests in the Irkutsk region. Pest distribution areas were evaluated in accordance with GOST 34 309–2017 and phytosanitary monitoring methods. Initial data for estimating economic losses was obtained from statistical data from the Federal Customs Service of Russia[5] and the administration of the Irkutsk region for 2020–2022[6, 7].

Phytosanitary risk assessment was carried out according to GOST 34 309–2017 and the methodology agreed upon by the phytosanitary control authority according to the algorithm below[8] (Fig. 1).

For the analysis, we used the results of a survey conducted in the Irkutsk region between 2021 and 2023, which was carried out with the participation of the authors. The survey included the identification of harmful insects and the determination of their distribution areas according to GOST 34 309–2017, as well as the methodology agreed upon by the phytosanitary control authorities. In addition, we used data from official statistics from the Federal Customs Service of Russia covering the period 2021 to 2023[9].

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[2] *On Plant Quarantine*. Federal Law No. 206–FZ dated 21.07.2014. Consultant plus. URL: https://www.consultant.ru/document/cons_doc_LAW_165795/ (accessed: 08.02.2024). (In Russ.).

[3] GOST R 57 973–2017. *Sanitary Safety in Forests. Terms and Definitions*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200157752 (accessed: 08.02.2024). (In Russ.).

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[5] *Russia's Exports of the Most Important Goods. Tables.* Customs statistics. Federal Customs Service. URL: https://customs.gov.ru/statistic/eksport-rossii-vazhnejshix-tovarov (accessed: 20.02.2024). (In Russ.).

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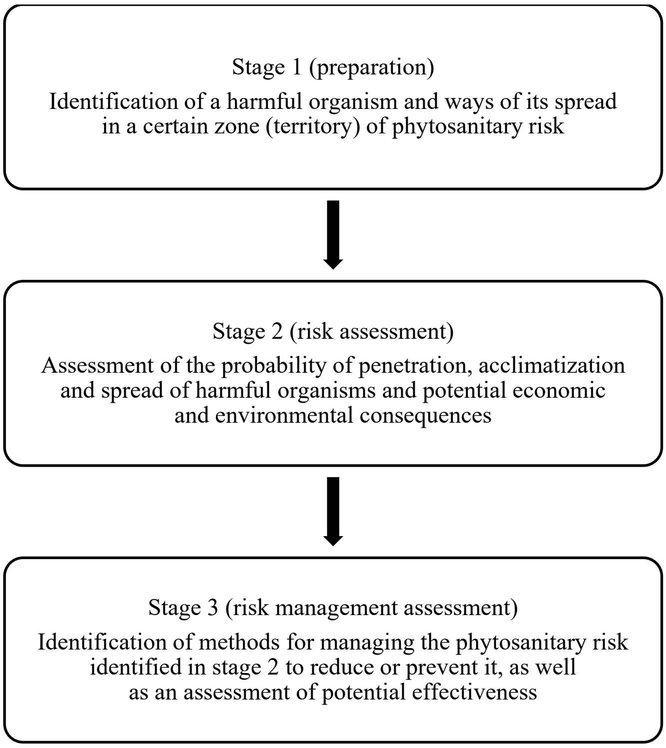

Fig. 1. Algorithm for phytosanitary risk assessment

The objects of research were:

– *Monochamus galloprovicialis Oliv.*, which causes a disease known as "blue timber". The presence of pests was assessed by the presence of holes and beaten flour in August;

– *Dendrolimus sibiricus*, which is a needle-eating insect and destroys coniferous forests. The appearance of 300 needle-eating 500 insect individuals on one tree was enough for its complete desiccation. The appearance of caterpillars was assessed in late July and early August[10];

– *Polygraphus proximus Blandford*, relates to bark beetles, leading to damage to the bark of coniferous trees, accompanied by redness and shrinkage, is able to survive at low temperatures up to –50°C.

The number of beetles on one infected tree in the foci of invasion could range from several hundred to several thousand individuals[11]. The presence of pests was recorded by the presence of gnawed channels on weakened and shrinking trees [5].

The assessment of potential damage (PD) for a given period of time was determined by the following formula:

$$\mathrm{PD} = \frac{\mathrm{VP} \cdot \mathrm{VA} \cdot \mathrm{PEV}}{100};$$

where VP — indicator of the probability of invasion; VA — indicator of the probability of acclimatization; PEV — indicator of potential economic harmfulness [11].

Determination of the density of infestation of timber with harmful insects was performed according to a well-known technique[12]. The number and method of sampling were determined in accordance with GOST 12 430–2019[13].

The results were processed using mathematical methods based on correlation and regression estimation.

Results. When conducting monitoring studies with the authors' participation in the Irkutsk region, several sites were identified where certain harmful insects, such as *Dendrolimus sibiricus, Polygraphus proximus, Monochamus sutor, Monochamus sartor, Monochamus, Monochamus impluviatus* were actively multiplying. The largest area of damage was caused by foci of *Dendrolimus sibiricus* (up to 92%).

[10] All-Russian Plant Quarantine Center STO 2.016–2016. *Dendrolimus Sibiricus Tschetverikov. Rules for Conducting Quarantine Phytosanitary Inspections of Quarantined Facilities and Establishing a Quarantine Phytosanitary Zone and Quarantine Phytosanitary Regime.* URL: https://oi25.vniikr.ru/documents (accessed: 08.02.2024). (In Russ.).

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During the surveys, *Abies sibirica* lesions were recorded by *Polygraphus proximus*, an invasive organism in this area. Outbreaks of mass reproduction of this organism can cause serious damage to *Abies sibirica*, which is one of the most important species of coniferous trees and is widely in demand in the international timber market, occupying a small area in the Irkutsk region. During a detailed examination of fir trees and their assessment based on the scale of damage caused by *Polygraphus proximus*, only 20% were found to be healthy, 40% weakened, and 15% severely weakened in the surveyed area. Figure 2 shows the distribution of *Abies sibirica* trees according to categories of condition based on damage caused by *Polygraphus proximus*[14]. The calculation was done using a well-known method[15]. It was established that there was up to 10% of dead wood on the surveyed territory.

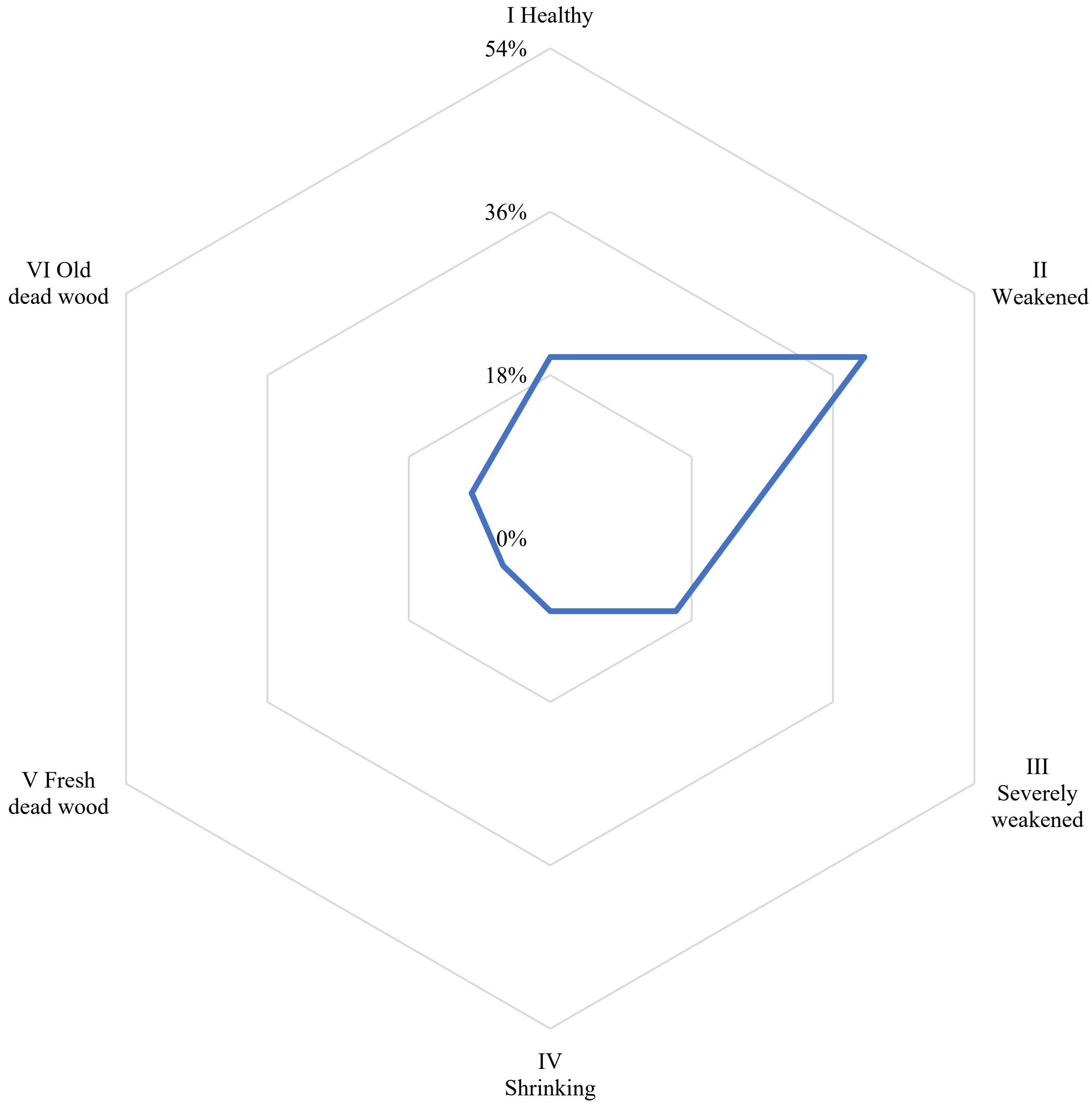
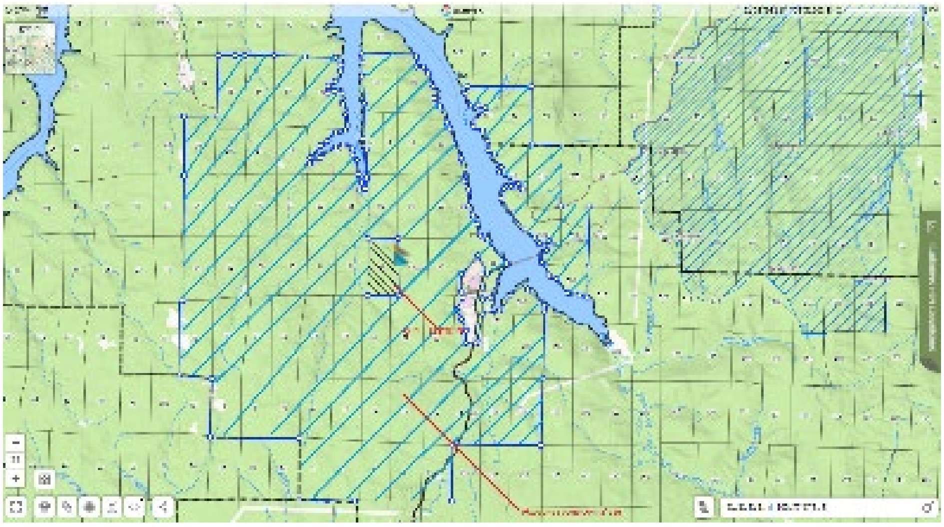


Fig. 2. Categories of condition of *Abies sibirica* trees damaged by *Polygraphus proximus*

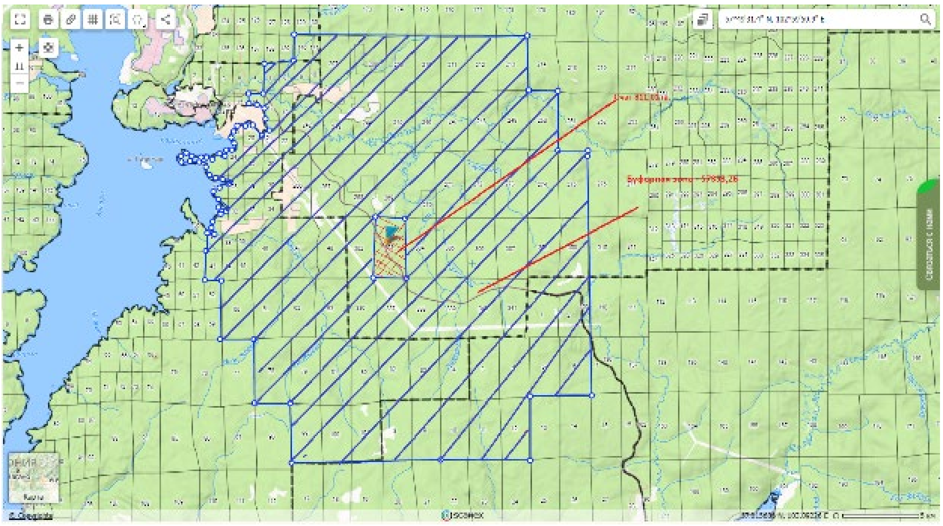
During monitoring studies in the summer-autumn period of 2023 in the Ust-Ilimsky district of the Northern forestry region, populations of the quarantine insect pest *Dendrolimus Sibiricus Tschetverikov* were identified in the following locations: Tubinsky district forestry: center area — 758.13 hectares; Sosnovsky district forestry: center area — 811.01 hectares Phytosanitary risk areas have been calculated for each site, as shown in Figure 3 and Table 1.

[14] *The Ussuri Polygraph in the Forests of Siberia (Distribution, Biology, Ecology, Identification and Inspection of Damaged Plantations).* Methodical manual. Tomsk-Krasnoyarsk: UMIUM; 2015. 48 p. (In Russ.).
[15] Id. P. 3–46.

a)

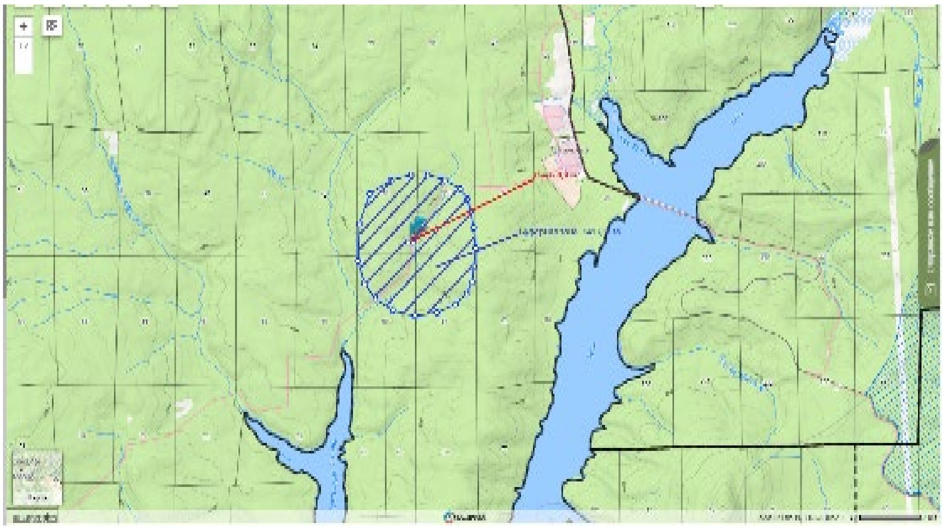


b)

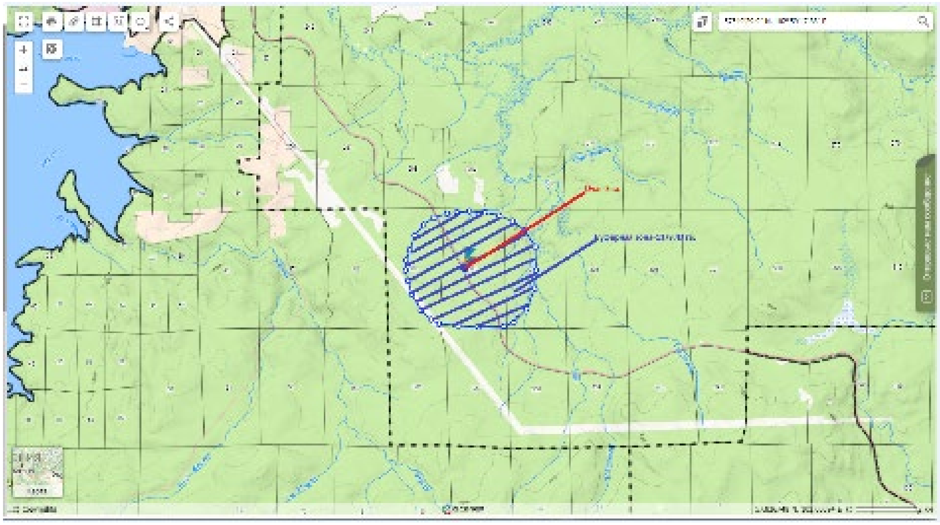


c)

Fig. 3. Phytosanitary risk zone in the forest areas of the Northern forestry on *Dendrolimus Sibiricus Tschetverikov*:
a — Northern forestry, Tubinsky district forestry, Kedrovskaya dacha, 43 quarter-center;
b — Northern forestry, Tubinsky district forestry, Tubinskaya dacha, 116 quarter-center;
c — Northern forestry, Tubinsky district forestry, Kedrovskaya dacha, 303 quarter-center



a)



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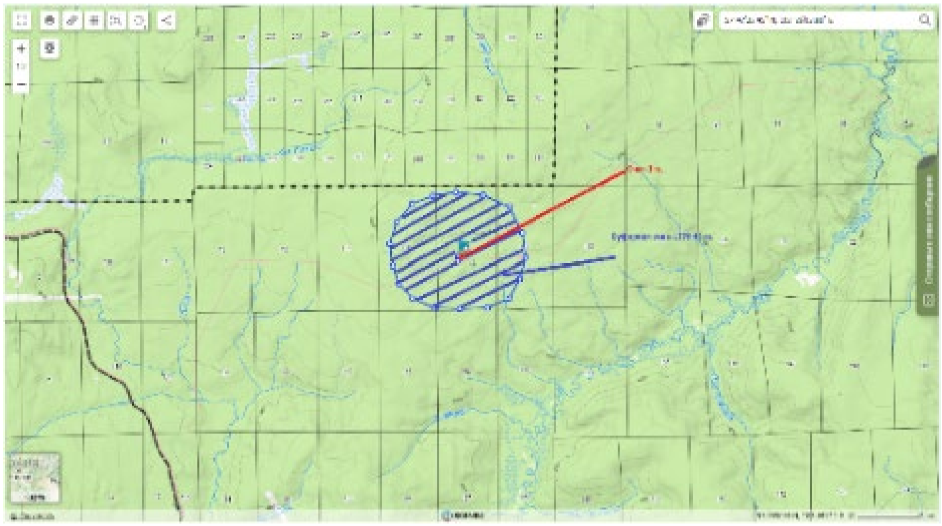

c)

Fig. 4. Phytosanitary risk zone in the forest areas of the Northern forestry on *Monochamus sartor*:
a — Northern forestry, Tubinsky district forestry, Kedrovskaya dacha;
b — Northern forestry, Sosnovsky district forestry, Karapchanskaya dacha;
c — Northern forestry, Tubinsky district forestry, Tubinskaya dacha

Table 1

Phytosanitary risk zones in the Northern forestry of Ust-Ilimsky district on *Dendrolimus Sibiricus*

Risk location	Phytosanitary risk zone, ha
43 quarters of the Northern forestry, Tubinsky district forestry	56,951.66
116 quarters of the Northern forestry, Tubinsky district forestry	57,180.09
303 quarters of the Northern forestry, Tubinsky district forestry	57,353.26

Lesions of *Monochamus urussovi Fisch* and *Monochamus galloprovincialis Oliv.* were found on the territory of the same forestry. Figure 4 and Table 2 provide phytosanitary risk zones for these insects.

Table 2

Phytosanitary risk zones in the Northern forestry of the Ust-Ilimsky district on *Monochamus urussovi Fisch*

Risk location	Phytosanitary risk zone on *Monochamus galloprovincialis Oliv.*, ha	Phytosanitary risk zone on *Monochamus urussovi Fisch*, ha
Northern forestry, Tubinsky district forestry, Kedrovskaya dacha	1,379.43	1,343.18
Northern forestry, Tubinsky district forestry, Tubinsky dacha	1,706.38	1,266.66
Northern forestry, Sosnovsky district forestry, Karapchanskaya dacha	1,821.96	1,263.73

The area of quarantine pest foci that were in the Irkutsk region in 2023 was 76,752.4 hectares. Of this area, foci of *Dendrolimus Sibiricus Tschetverikov* accounted for 92%.

During the customs inspection of wood prepared for export from these forest areas, larvae of *Monochamus galloprovincialis Oliv., Dendrolimus Sibiricus Tschetverikov*, and *Polygraphus proximus Blandford* were found. Calculations have established that the density of distribution of live larvae could reach 540 m^3 of quarantined products, which went beyond the entire volume of production, i.e. the spread of the pest would move to neighboring areas located near logging facilities.

Within the phytosanitary risk zones, the activities of loggers and the export of wood outside the established zone were limited.

Economic losses from the under-supply of wood and the implementation of phytosanitary risks within the studied forestry amounted to 1,276 thousand dollars when exported to China at an average price of 220 dollars per 1 m^3 of coniferous wood.

Discussion and Conclusion. It has been shown that in 2023, on the territory of the Irkutsk region, an unfavorable situation has developed and high phytosanitary risks have been recorded for several pests, including *Dendrolimus sibiricus, Monochamus galloprovicialis Oliv., Monochamus sartor* and *Polygraphus proximus Blandford*.

Ust-Ilimsky district ranked first among the surveyed territories in terms of the total area affected. The largest breeding sites of *Dendrolimus sibiricus* were recorded in the Tubinsky forestry district. The phytosanitary risk areas for *Monochamus galloprovicialis Oliv.* accounted for 2.7% of the total affected area and were mainly concentrated in the Sosnovsky forestry district. The area affected by *Monochamus sartor* reached 2.1% of the total and was recorded in Tubinsky forestry and Kedrovskaya dacha. In Tubinsky forestry, there were foci of an invasive and highly aggressive species — *Polygraphus proximus Blandford* — affecting fir trees over an area of 0.8%. Therefore, special attention must be paid to preventive measures against this pest.

Considering that forestry enterprises in the Ust-Ilimsky district are the suppliers of raw materials for the timber industry and exporters of wood products, the establishment of significant quarantine zones and restrictions on the export of timber causes significant damage to the budget of the Irkutsk region. Pine is the most popular type of wood for export, accounting for an average of 75% of the total volume, followed by Siberian fir at 7%. In this regard, it is essential to monitor fir trees in three categories: operational — for the detection of shrinking trees during forestry rounds; regime — at stationary sites in damaged areas; and local — in areas with the highest incidence of shrinkage. If more than 10% of Category IV trees are identified, sanitary felling should be conducted to prevent the outbreak of pest infestation. Category V and VI trees should be felled for firefighting purposes.

To combat *Dendrolimus sibiricus*, which can be found in coniferous forests, we recommend using a biological preparation called "Lepidocide®", which is based on the *Bacillus thuringiensis var.kurstaki* strain. This preparation contains spores and cells from *Bacillus thuringiensis var. kurstaki* culture producer, as well as delta-endotoxins in the form of protein crystals and inert fillers to ensure the safety and stability of the product. The drug is safe for humans and warm-blooded animals, and the death of insects occurs only after the drug enters their intestines. The recommended dosage of "Lepidocide®" is 3 liters per hectare. It can be applied as a suspension during aerial treatment of forests using low-volume or ultra-low-volume spraying methods, or through aerosol sprayers using adjustable dispersion generators.

The experience of combating *Dendrolimus sibiricus* in the Irkutsk region during 2016–2017 using new insecticides "Clonrin CE" and "Clipper CE" has shown that the processing of timber harvested for export in warehouses, although ensuring its safety, can lead to unpredictable environmental consequences.

Given the unfortunate experience of widespread and careless use in the 1960s and 1970s of DDD — 1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane, a persistent organic pesticide that is still present in biota and accumulates in trophic chains, and is found in Antarctic penguin fat tissue, it is important to avoid using "Clonrin CE", despite the recommendations of relevant authorities[16].

For preventive purposes, it is recommended to install pheromone traps to monitor for pests. The traps should be placed at a height of 1.5–2 meters above the ground in the early summer and checked periodically.

The current situation regarding the spread of quarantine insects in the forests of the Irkutsk region is considered unfavorable and requires the compliance with preventive and response measures in the event of an increase in numbers or the emergence of new outbreaks. The most environmentally friendly option for managing these risks is to conduct sanitary logging, which includes timely removal of wind- and fire-damaged trees and the installation of pheromone traps. Additionally, treatment with biological products can help control the spread of pests.

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SV Tenchikov: calculations, analysis of the research results, formulation of the conclusions.

SS Timofeev: calculations of potential damage to the economy of the region.

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Research Article

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Use of Artificial Intelligence to Monitor the Reliability of Removable Load-Handling Devices

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Abstract
Introduction. The malfunction of removable load-handling devices (RLHD) poses significant production risks. That is why research in this field is relevant. The problem has often become a topic of scientific investigation. The authors propose using artificial intelligence more extensively to monitor the state of RLHD. This paper presents a study on how to improve the machine vision model to better identify the absence of locks on RLHD hooks. A probable occurrence of such an issue in production is noted. A storage and monitoring system for RLHD condition is proposed. The aim of this study is to demonstrate the potential for further training of neural networks to significantly enhance the efficiency of RLHD monitoring, ensuring their safe use.
Materials and Methods. The work is based on the results of a survey conducted at the LLC "KZ Rostselmash" plant from 2022 to 2023, involving 144 RLHD. Mathematical statistics methods were used to process the data. A neural network model previously trained using the YOLO computer vision algorithm was studied. It was retrained taking into account the norms of the rejection of RLHD, specified in federal rules and standards. Images of RLHD with defects and missing parts were collected from these sources and used to create a training database. The database was expanded by augmentation. The Roboflow platform was used for work.
Results. The array of images used for further training of the neural network was divided into three samples: training (88%), validation (8%) and test (4%). These samples were used to train and validate its results. The training was completed after 260 epochs, with a steady increase in accuracy. The neural network model of computer vision obtained in this way automatically detected a common defect in the RLHD hook — the absence of a lock. Its performance was assessed using three indicators: average accuracy (94%), prediction accuracy (88.8%) and response (89.2%). The neural network could receive images from a video camera in real-time and recognize hook defects. During the RLHD inspection at the Rostselmash plant, a grab for lifting engines was found to have all three hooks defective — without locks. To avoid such situations, at the end of work, it was recommended to place the RLHD on a special stand equipped with a microcontroller device that could monitor for a number of potential issues using radio frequency identification.
Discussion and Conclusion. The main goal of this proposed solution is to detect and address signs of non-compliance with the established standards. This task can be implemented in facilities that use lifting equipment. In this case, the timely noticed RLHD defects will allow preventing production incidents. As a result, material damage can be reduced and injury statistics improved.

Keywords: monitoring the condition of removable load-handling devices, rejection of load-handling devices, defects of hooks for cargo work

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Научная статья

Использование искусственного интеллекта для контроля надежности съемных грузозахватных приспособлений

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Аннотация
Введение. Неисправность съемных грузозахватных приспособлений (СГП) создает значимые производственные риски. Этим обусловлена актуальность исследований в данном направлении. Проблема часто становится темой научных изысканий. Авторы предлагают шире использовать искусственный интеллект для мониторинга состояния СГП. В представленной работе показано, как усовершенствовать модель машинного зрения для лучшего выявления отсутствия замков на крюках СГП. Отмечена вероятность широкого распространения проблемы в производственной практике. Предложена схема стенда хранения и контроля состояния СГП. Цель исследования — продемонстрировать возможности дообучения нейросети для существенного повышения эффективности контроля СГП, обеспечивающего безопасность их применения.
Материалы и методы. Работа базируется на актах обследования 144 СГП на заводе ООО «КЗ «Ростсельмаш»» в 2022–2023 гг. Материалы обрабатывались методами математической статистики. Исследовалась нейросетевая модель, предварительно обученная по алгоритму компьютерного зрения YOLO. Ее дообучили с учетом норм браковки СГП, зафиксированных в федеральных правилах и стандартах. Из этих источников взяли изображения СГП с дефектами и отсутствующими элементами и сформировали базу для дообучения сети. Базу расширили методом аугментации. Для работы использовали платформу Roboflow.
Результаты исследования. Массив изображений для дообучения нейросети разделили на три выборки: обучающую (88 %), проверочную (8 %) и тестовую (4 %). По ним проводили обучение и верифицировали его результаты. Обучение завершилось за 260 эпох при стабильном увеличении точности работы. Полученная таким образом нейросетевая модель компьютерного зрения автоматически обнаруживает часто встречающийся дефект крюка СГП — отсутствие замка. Качество ее работы оценили по трем показателям: средняя точность (94 %), точность предсказания (88,8 %) и отклик (89,2 %). Нейросеть может в режиме реального времени получать изображение с видеокамеры и распознавать дефект крюка. При обследовании СГП на заводе «Ростсельмаш» обнаружили эксплуатируемый захват для подъема двигателей, у которого все три крюка оказались дефектными — без замков. Для исключения таких ситуаций по окончании работы целесообразно размещать СГП на специальном стенде с микроконтроллерным устройством, которое отследит наличие ряда проблем с помощью радиочастотной идентификации.
Обсуждение и заключение. Основное предназначение описанного решения — выявление и фиксация признаков несоответствия СГП требуемым нормативам. Задача может быть реализована на объектах, эксплуатирующих подъемные сооружения. В этом случае своевременно замеченные изъяны СГП позволят предупреждать производственные инциденты. В итоге можно рассчитывать на снижение материального ущерба и улучшение статистики по травматизму.

Ключевые слова: контроль состояния съемных грузозахватных приспособлений, браковка грузозахватных приспособлений, дефекты крюков для грузовых работ

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Introduction. The sites where lifting cranes and other types of cranes are used are considered hazardous production facilities (HPF)[1] and must comply with strict safety regulations. This includes safe operation of the equipment complex and its elements, such as removable load-handling devices (RLHD). The health of this system depends to some extent on human factors [1], and the risks associated with these operations can be reduced by introducing automation and digital solutions.

HPF activities are under the supervision of the Federal Service for Environmental, Technological and Nuclear Supervision (Rostechnadzor). At the same time, lifting structures and their associated equipment are exempt from regular inspections[2], and the condition of the equipment is monitored by relevant services within the operating enterprises [2].

Rostechnadzor publishes annual statistics on accidents and incidents, as well as conclusions based on the results of its investigations[3]. These materials help us identify the main causes of accidents, particularly those related to the monitoring of the condition of lifting devices. Some of the main causes include:

– absence of designated specialists responsible for the safe operation of lifting devices;

– admittance to work of personnel without appropriate qualifications;

– absence of job descriptions and production instructions at the facility;

– untimely scheduled inspections, repairs and technical inspections of lifting devices and equipment working in conjunction with them.

Slingers use removable devices to hang loads from the hooks of lifting cranes or crane manipulators. The trouble-free operation of the facility depends on the accuracy of these procedures.

Lifting structures should only be used in work projects or with technological maps, which include a mandatory element — a cargo slinging scheme[4]. Before starting work, slingers, crane operators, and specialists responsible for safe work production get familiar with the technological maps with provision of signature upon familiarization. The slinging systems are posted at the work site.

The second important safety factor is the condition of the RLHD equipment. RLHD malfunctioning can lead to falling of goods, lifting devices, or their components. Additionally, the stability of the lifting structure can be compromised, which can result in material losses and injury to personnel.

Regulatory legal acts and job descriptions specify the requirements for continuous monitoring of the RLHD condition. According to these documents:

– the slinger is responsible for daily monitoring of the RLHD condition, for which they are given time prior to starting work[5];

– at least once every 10 days, the specialist responsible for the safe operation of lifting structures monitors the condition of slings. At least once a month, they also monitor grabs and traverses.

The results of the inspections are recorded in the logbook of periodic inspections of removable lifting devices and containers.

The fulfillment of these requirements should exclude the possibility of using faulty, defective RLHD.

It is known from statistics and literature [2] that the accident rate at HPF depends on the qualifications of managers and responsible specialists. Personnel with insufficient competencies [3] may neglect control, skip some stages, and violate the rules of RLHD inspections and documentation of their results.

The correct use of artificial intelligence greatly enhances the effectiveness of RLHD control.

This article explores the potential of further training neural networks [4] in order to improve the accuracy of monitoring the RLHD operational state. We propose introducing neural network-based computer vision technologies [5] for monitoring the operability of hooks on removable load-handling devices.

This approach is in line with the National Strategy for the Development of Artificial Intelligence for the period up to 2030[6].

The aim of this study is to explore the potential for further training of a neural network in order to enhance the capabilities of machine vision for determining the RLHD suitability. The practical application of this proposed solution has the potential to improve the efficiency of monitoring the RLHD status and, consequently, enhance the safety of their usage.

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[1] *On Industrial Safety of Hazardous Production Facilities.* Federal Law No. 116-FZ dated 21.08.1997. Consultant Plus. URL: http://www.consultant.ru/document/cons_doc_LAW_15234/ (accessed: 18.03.2024). (In Russ.).

[2] Id.

[3] Rostechnadzor. *Report on the Activities of the Federal Service for Environmental, Technological and Nuclear Supervision in 2022*. URL: https://www.gosnadzor.ru/public/annual_reports (accessed: 10.03.2024). (In Russ.).

[4] *On the Approval of Federal Norms and Rules in the Field of Industrial Safety "Safety Rules for Hazardous Production Facilities where Lifting Structures are Used"*. Rostechnadzor Order No. 461 dated 26.11.2020. Garant. URL: https://base.garant.ru/400165076/ (accessed: 10.03.2024). (In Russ.).

[5] *Standard Instruction for Slingers on the Safe Production of Work by Lifting Machines (RD 10-107-96).* Garant. URL: https://base.garant.ru/3924623/ (accessed: 10.03.2024). (In Russ.).

[6] *National Strategy for the Development of Artificial Intelligence for the Period up to 2030.* Consultant Plus. URL: https://www.consultant.ru/document/cons_doc_LAW_335184/ (accessed: 10.03.2024). (In Russ.).

Materials and Methods. Slings are designed to hook, strap and hold cargo on the hook of a lifting device [6]. Different methods of sling rejection are used, depending on the design of the sling and the material it is made from. The standards for sling rejection are defined in relevant documents. The test methods are described in the state standards[7].

Each sling must have a marking tag indicating the manufacturer, serial number, load capacity and test date. The absence of a tag is unacceptable and is an indication of a defect. An important element of the RLHD and slings is a hook with a mandatory locking device (hook lock) [7].

In preparing this article, we used mathematical statistics to analyze the results of a mass RLHD survey conducted at the LLC "KZ "Rostselmash" plant in Novocherkassk in 2022 and 2023. The survey was conducted by specialists from the engineering consulting center "Mysl"", which was affiliated with Novocherkassk State Technical University. The results of the survey were compiled in the form acts — mandatory appendices to the passports of each RLHD. These documents were the source materials of the presented scientific work (Fig. 1, 2).

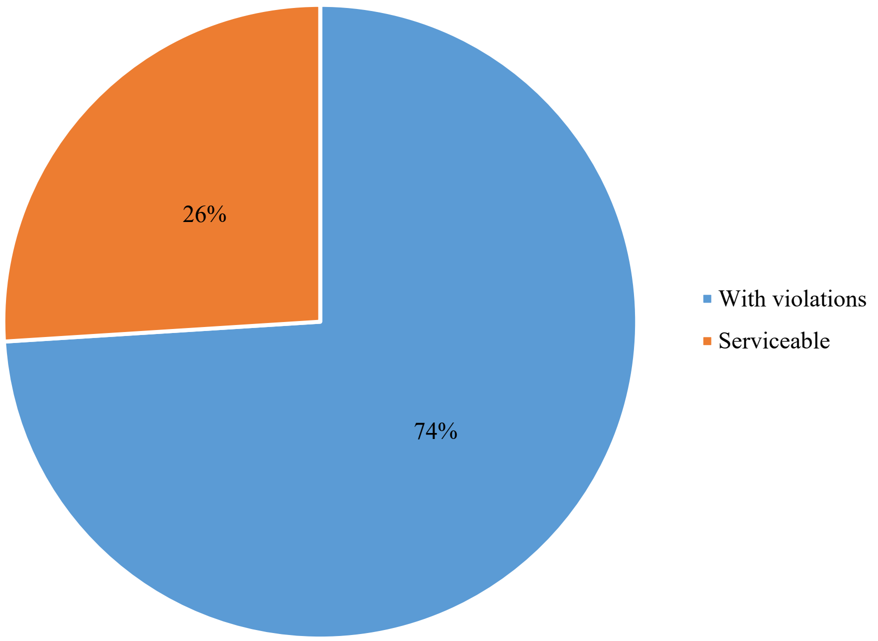

Fig. 1. Ratio of serviceable and non-serviceable RLHD

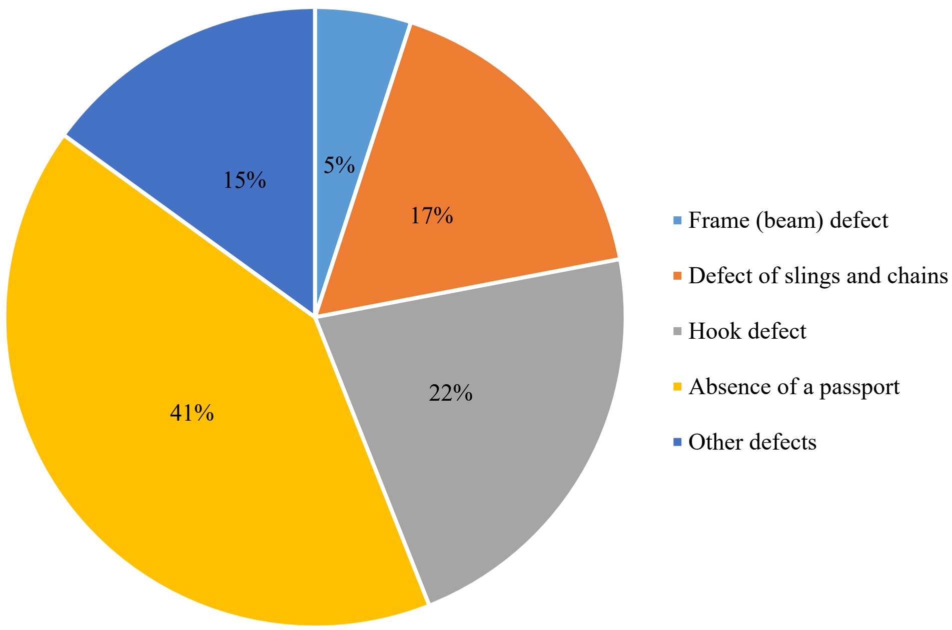

Fig. 2. Proportion of RLHD with inconsistencies and defects

[7] GOST 33715-2015. *Cranes. Non-Fixed Load-Lifting Attachments and Tare. Exploitation.* Garant. URL: https://base.garant.ru/71684432/ (accessed: 10.03.2024). (In Russ.).

According to the survey of 144 RLHD, three quarters of the devices did not meet the requirements of regulatory documentation[6] (Fig. 1).

The analysis of the distribution of defects and inconsistencies in regulatory documentation showed that the absence of an RLHD passport was most common (more than 40% of cases). The most common technical flaw was a hook defect (22% of cases). Defects in chains and slings accounted for 17% of recorded cases, and other defects accounted for 15%. Structural defects amounted to 5%. These were flaws in special grips, pins, clamps, frames, beams, and traverses.

It is advisable to start the study with questions of monitoring the condition of hooks. In almost 100% of cases, their defects were the absence or breakdown of the sling retainer (lock).

In [8], the possibilities of integrated risk assessment in the diagnosis of steel ropes using computer vision are explored. This approach has become the basic one in the development of methods for quickly identifying nonconformities and malfunctions of the RLHD. Devices that do not meet the required standards should not be permitted to operate. To this end, technical control must be strengthened through a digital monitoring system equipped with computer vision that can automatically detect visually identifiable malfunctions.

Based on the results of the comparative analysis, one of the computer vision algorithms was chosen — the pre-trained YOLOv8 open access neural network[8]. This was the latest version of a well-known model for real-time object detection and image segmentation. It was based on the latest advances in deep learning and computer vision and had high performance in terms of speed and accuracy. Due to its design features, it was suitable for various applications and adapted easily to different hardware platforms. YOLOv8 identified many real-world objects: people, cars, computers, pieces of furniture, etc. However, YOLOv8 needed additional training to detect RLHD [9]. It was performed using the open online service Roboflow[9], which provided the user with tools to create a database of annotated images necessary for training the YOLOv8 model. The service allowed you to upload and annotate images by specified classes, assign them to train, validation and test samples [10].

Results. To retrain the network, unannotated images of hooks of different types, sizes and shapes with and without a lock (Fig. 3) were used. These images were collected from various sources, including during the RLHD examination.

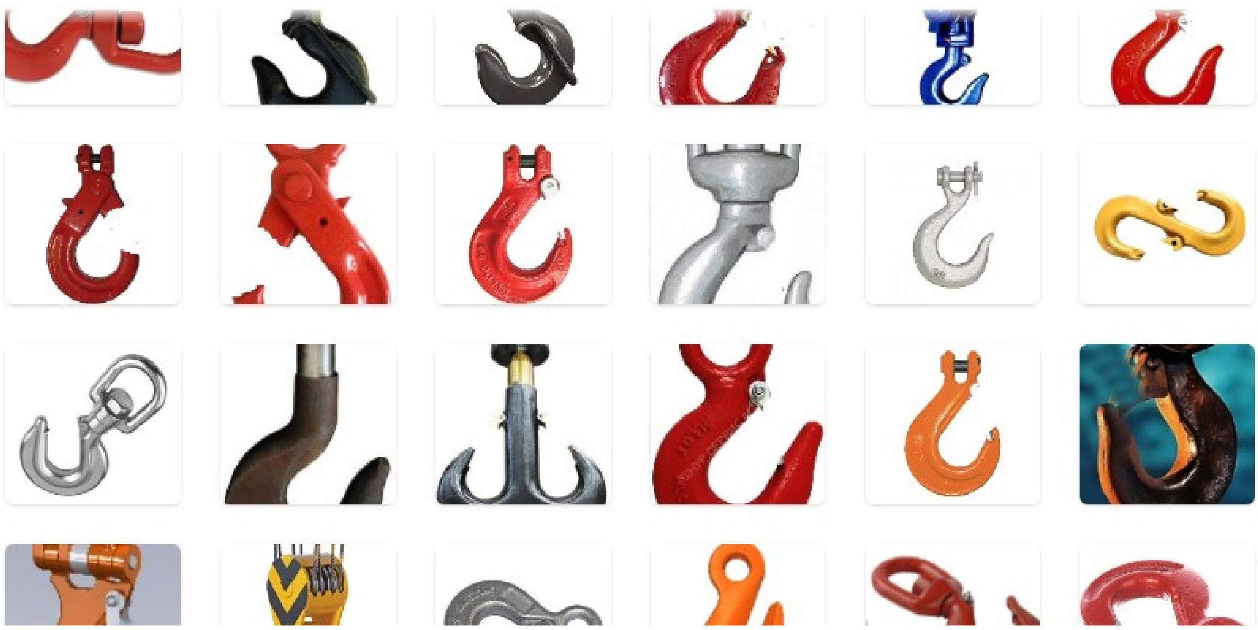

Fig. 3. Images of hooks without locks uploaded to the Roboflow service

The variety of hook images improved the quality of learning and subsequent recognition, significantly reduced the number of errors of the pre-trained model [11].

At the next stage, the contours of the recognition objects were selected using the smart polygon tool and annotated according to the hookWithLock (for hooks with a lock) and noLock (for hooks without a lock) classes (Fig. 4).

[8] *Introducing Ultralytics YOLOv8.* Ultralytics. URL: https://docs.ultralytics.com/ (accessed: 10.03.2024).
[9] *Everything You Need to Build and Deploy Computer Vision Models.* Roboflow. URL: https://roboflow.com/ (accessed: 10.03.2024).

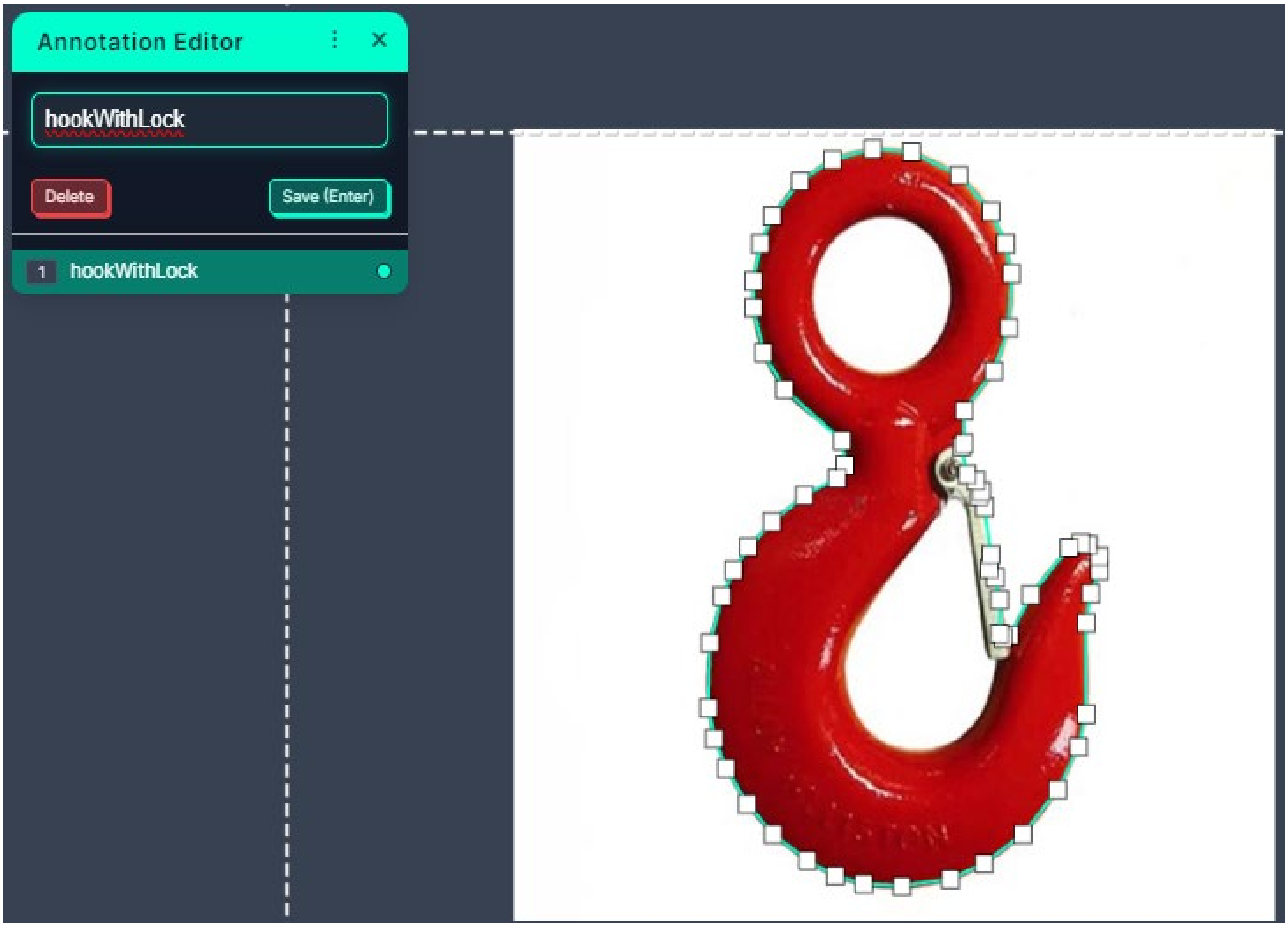

Fig. 4. Annotating the image

The next stage in the additional training process for the neural network in Roboflow was augmentation, i.e. increasing the sample size by converting images. Perspective, noises, turns, etc. were used for this purpose. As a result, 401 annotated images were obtained (Fig. 5)

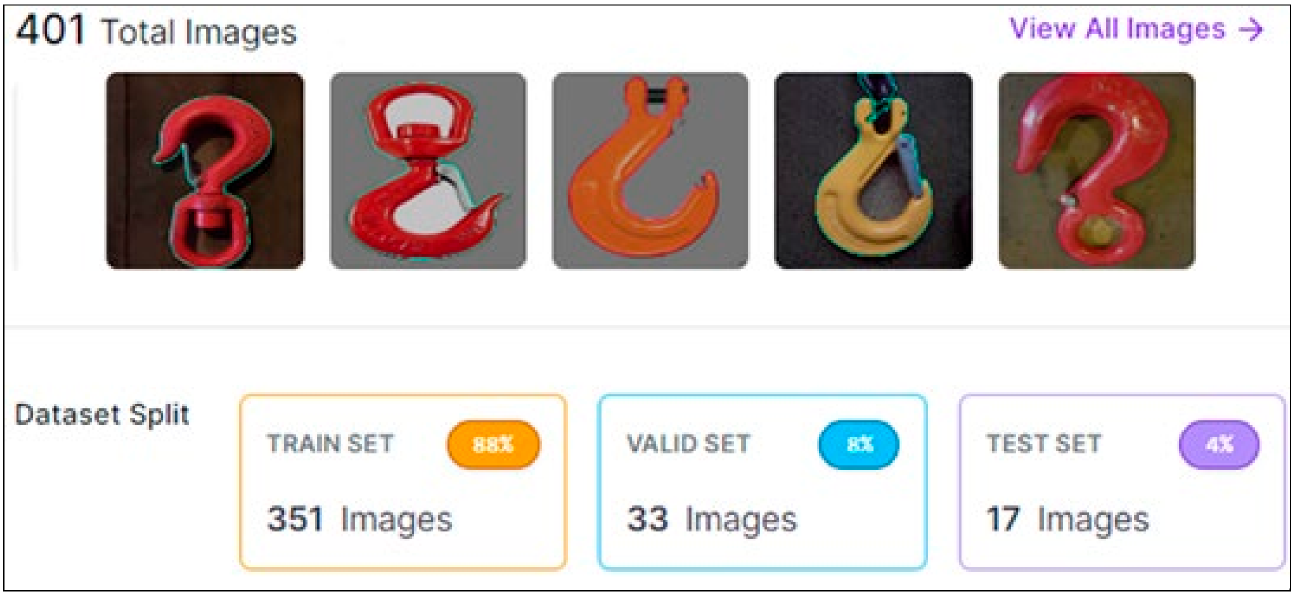

Fig. 5. The result of annotation and augmentation

The resulting array of images was divided into train set, valid set and test set in the ratio of 88%, 8% and 4%, respectively. Samples were used for network training and verification of learning outcomes [12].

The network trained and compared the results with a valid sample. At the same time, the accuracy of its work steadily increased, and the training was completed in 260 epochs (Fig. 6).

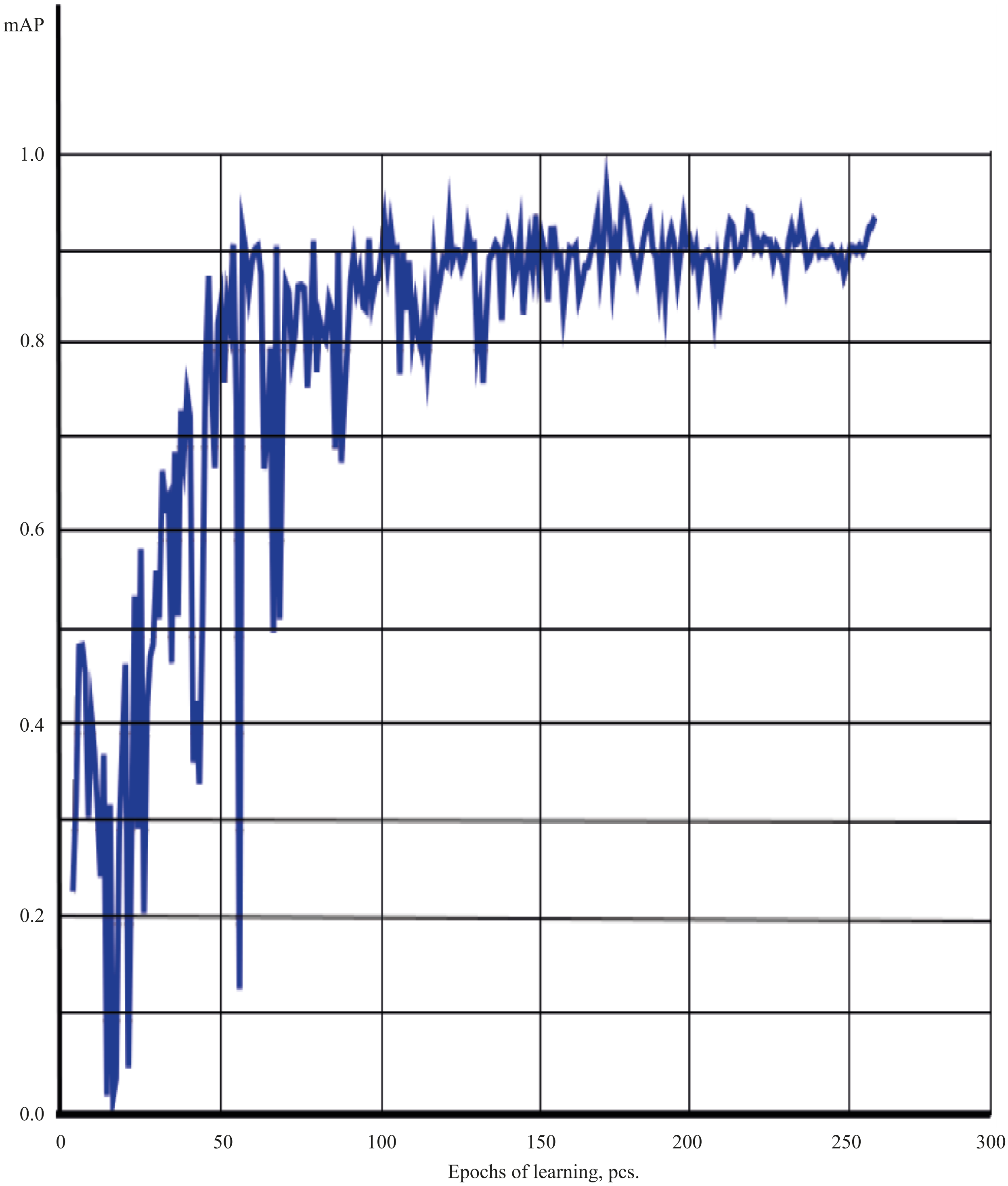

Fig. 6. Changes in the accuracy of computer vision neural network in the learning process

As a result, we obtained a neural network model of computer vision, which automatically detected a common defect of the RLHD hook — the absence of a lock. The quality of its work was assessed by three indicators described below (Fig. 7)

Fig. 7. Indicators of the quality of training of the resulting neural network

1. Average precision value (mAP), equal to the average value of the average accuracy index for all classes in the model. In this case, it was 94%.

2. Precision of prediction — showed how often the model's predictions turned out to be correct. The fixed level was 88.8%.

3. Recall — the percentage of successfully identified tags. It was 89.2%.

Such a neural network could receive a real-time image from any video camera and recognize a hook defect (Fig. 8)

a)

b)

Fig. 8. Work of a pre-trained neural network to detect hooks: *a* — with a lock; *b* — without a lock

This neural network was easily embedded in the program code in any programming language. This made it possible to create a software product for automated assessment of the presence of RLHD defects and implement it into a production digital system for monitoring the RLHD condition [13].

During the RLHD inspection at the LLC “KZ “Rostselmash”” plant, a PM-001501 grab was found. The device was manufactured by the production company “Pod’em-master” and was designed for lifting engines of the Yaroslavl Motor Plant. It could serve as an example of the operation of a faulty RLHD (Fig. 9).

Fig. 9. PM-001501 grab without locks on hooks

As you can see, there were no mandatory locks on all three hooks. Nevertheless, the device was operated, which posed risks to the life and health of personnel, as well as endangered the integrity of technical facilities. It was logical to assume that such elements were in operation at many enterprises in Russia. To avoid such situations, the authors of this article proposed to place the RLHD on a special stand at the end of the work (Fig. 10).

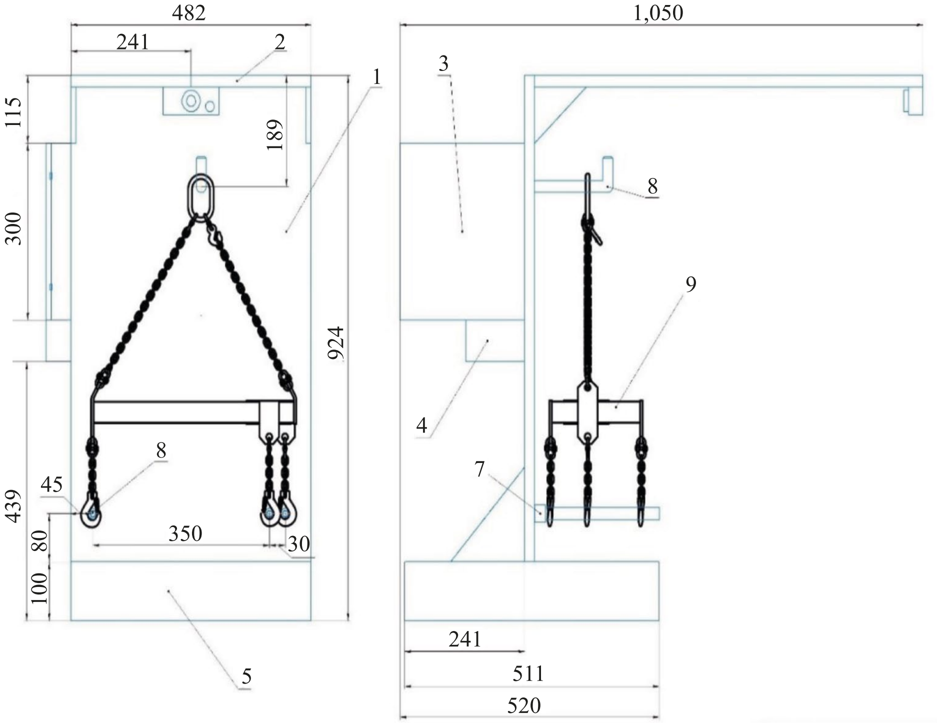

Fig. 10. Stand for storage and monitoring of the RLHD condition: 1 — stand; 2 — bracket with camera; 3 — box for RLHD passport; 4 — electronic unit; 5 — base; 6 — hook pin; 7 — insulator; 8 — hanger; 9 — removable load-handling device

The stand was equipped with a microcontroller device that monitored the availability of the RLHD passport using an RFID tag (radio frequency identification). In addition, it was used to determine the correct placement of hooks on the stand. The tactile pins of the ESP32 controller were used for this purpose. When the hooks were positioned correctly, their condition was recorded by a camera [14] mounted on the stand bracket. The resulting image was interpreted by a trained neural network model of computer vision and a preliminary conclusion was drawn on the presence or absence of a defect [15].

Discussion and Conclusion. The proposed software and hardware solution is designed for automated assessment of the condition of RLHD elements of operated lifting cranes. Using the potential of artificial intelligence improves the quality and efficiency of monitoring. In particular, it allows timely identification of the lack of necessary elements and defective indicators of the RLHD. This opens up the possibility of a significant reduction in accidents. Adequate implementation of the proposed approach in production practice will also ensure informed decision-making regarding extending the service life, admission to further operation or rejection of the RLHD.

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AA Korotkiy: generalization of the research results, formulation of the conclusions.

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Research Article

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Comparative Analysis of the Performance of Artificial Neural Networks in Assessing the Technical Condition of Steel Ropes

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Abstract

Introduction. Currently, artificial neural networks (ANN) are successfully used for technical diagnostics of steel ropes. Expensive software products with an adapted neural network implementation environment, such as STATISTICA, Amygdala, MatLab Simulink, are often used for this purpose. The most affordable way to build and train an ANN, from a financial point of view, is to write your own program code using interactive libraries such as TensorFlow, PyTorch, Scikit-learn. However, such libraries are not fully adapted for building an ANN, and to use them you need to have basic programming skills. As a result, the quality of an ANN depends not only on its architecture, training data, and composition, but also on the environment in which it is built. The aim of the work was to compare the quality of the ANN, built and trained by various methods according to the criterion of test network performance, confidence levels for assessing the technical condition of the rope, as well as the complexity and speed of training. For this purpose, new software has been developed to solve the problem of assessing the technical condition of a steel rope using a combination of various rejection indicators.

Materials and Methods. The basis for an ANN training was a statistical database of typical damages of steel ropes and, an expert assessment of the technical condition of steel ropes. The software was written in the Python programming language. Various methods of programming a neural network were presented: an ANN built on the basis of the STATISTICA software package and an ANN built using the interactive Scikit-learn library. Ten test samples were prepared to verify the operation of the ANN. The ANN quality was assessed based on the test network performance and confidence probabilities (activation levels of the "winning" neuron) of determining the technical condition of the rope.

Results. The construction of the ANN using the interactive library Scikit-learn showed a relatively high complexity of construction and a relatively low learning rate of the ANN. Test performance of the network, with a test sample size of ten, turned out to be the same for both built ANNs. At the same time, there was a difference in the indicator of the average confidence level for determining the technical condition of a steel rope between the results of the ANN built on the basis of the STATISTICA software package and the ANN built using the Scikit-learn interactive library.

Discussion and Conclusion. The results showed that the ANN built using the STATISTICA software package with the same architecture and network learning parameters had more optimal software algorithms according to the criteria of confidence probability and network learning speed in comparison with the ANN built using the free Skicit-learn library. However, the indicator of the ANN test performance turned out to be the same for both ANNs. This result justified the use of TensorFlow, PyTorch, and Skicit-learn libraries by the world's leading research and commercial centers in the field of artificial intelligence. The obtained scientific result allows us to numerically evaluate and compare the quality of an ANN having the same architecture and learning parameters, but built using different methods. This will be useful for future scientific research in the field and for selecting the optimal environment for constructing ANNs in industrial applications.

Keywords: steel rope, artificial neural networks, technical condition assessment, Python, Skicit-learn, STATISTICA, rejection indicators

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Научная статья

Сравнительный анализ качества работы искусственных нейронных сетей для оценки технического состояния стального каната

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Аннотация

Введение. В настоящее время искусственные нейронные сети (ИНС) успешно применяются для технического диагностирования стальных канатов. Зачастую при этом используют дорогостоящие программные продукты с адаптированной средой реализации нейронных сетей, такие как STATISTICA, Amygdala, MATLAB Simulink. Наиболее доступным способом построения и обучения ИНС с финансовой точки зрения является написание собственного программного кода с использованием интерактивных библиотек, таких как TensorFlow, PyTorch, Scikit-learn. Однако такие библиотеки не являются полноценными адаптированными средами построения ИНС, и для их использования необходимо владеть первичными навыками программирования. Поэтому качество ИНС зависит не только от архитектуры, объема и состава обучающих выборок, но и от метода (среды) построения ИНС. Целью данного исследования является сравнение качества работы ИНС, построенных и обученных различными методами, по критерию тестовой производительности сети, доверительным уровням оценки технического состояния каната, а также трудоемкости и скорости обучения. В связи с этим создано новое программное обеспечение для решения задачи оценки технического состояния стального каната по комбинации различных браковочных показателей.

Материалы и методы. Основой для обучения ИНС послужили статистическая база данных типовых повреждений стальных канатов, экспертная оценка их технического состояния. Программное обеспечение написано на языке программирования Python. Приведены различные методы программирования нейронной сети: ИНС, построенной на базе программного комплекса STATISTICA, и ИНС, построенной с использованием интерактивной библиотеки Scikit-learn. Для проверки работы ИНС было подготовлено 10 тестовых выборок. Оценка качества работы ИНС проводилась по тестовой производительности сети и доверительным вероятностям (уровням активации «победившего» нейрона) определения технического состояния каната.

Результаты исследования. Построение ИНС с использованием интерактивной библиотеки Scikit-learn показало сравнительно большую трудоемкость построения и сравнительно небольшую скорость обучения. Тестовая производительность сети при объеме тестовой выборки 10 оказалась одинаковой для обеих построенных ИНС. При этом обнаружилась разница в показателе среднего доверительного уровня определения технического состояния стального каната по результатам работы ИНС, построенной на базе программного комплекса STATISTICA, и ИНС, построенной с использованием интерактивной библиотеки Scikit-learn.

Обсуждение и заключение. Полученные результаты показали, что ИНС, построенная с использованием программного комплекса STATISTICA, при одинаковой архитектуре и параметрах обучения сети имеет более оптимальные программные алгоритмы по критериям доверительной вероятности и скорости обучения сети по сравнению с ИНС, построенной с использованием бесплатной библиотеки Skicit-learn. Однако показатель тестовой производительности ИНС оказался одинаковым для обеих ИНС. Такой результат обосновывает использование ведущими мировыми научно-исследовательскими и коммерческими центрами в области искусственного интеллекта библиотек TensorFlow, PyTorch, Scikit-learn. Полученный научный результат позволит численно оценить и сравнить качество искусственных нейронных сетей, имеющих одинаковые архитектуру и параметры обучения, но построенных различными методами, он будет полезным как для будущих научных исследований в этой области, так и для выбора оптимальной среды построения ИНС в промышленной сфере деятельности.

Ключевые слова: стальной канат, искусственные нейронные сети, оценка технического состояния, Python, Scikit-learn, STATISTICA, браковочные показатели

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Introduction. Currently, methods for assessing the technical condition of engineering facilities using artificial neural networks (ANN) are becoming more widely used. This is due to the ease of identifying dependencies between the output data, which in this case is the technical condition of steel ropes, and the input data, which are various combinations of indicators that indicate defects in the steel ropes. To establish the correlation between the technical condition of a steel rope and various combinations of ten defective indicators expressed as a percentage of the permissible level of damage, a significant amount of analytical work and solving a multifactorial regression problem is required. Software that uses a neural network as its core can help experts and beginners in making decisions about the future operation of steel ropes based on different combinations of defect indicators.

Scientists from various fields of expertise are addressing the issues of reliability and safety in technical systems by employing modern artificial intelligence tools. Examples include the works of V.A. Vorontsov, E.A. Fedorov, A.A. Korotky, A.V. Panfilov, N.N. Nikolaev, A.R. Yusupov, S.V. Zhernakov, T.I. Goreva, N.N. Portyagin, G.A. Pyukke, B.Ch. Meskhi, A.N. Beskopylny, S.A. Stelmakh, I.F. Razveeva et al. [1–8]. These researchers successfully employ neural network modeling techniques to achieve various research and industrial objectives, such as evaluating the technical condition of aircraft engines and spacecraft systems, as well as detecting and classifying defects in steel ropes. At the same time, various architectures, ANN training parameters, software packages and artificial neural network development environments are used, such as Alyuda NeuroIntelligence, STATISTICA, Amygdala, and MatLab Simulink. It is also common practice to write your own program code using free (open-source) interactive libraries, such as TensorFlow, PyTorch, and Sikit-learn. However, it is worth noting that none of these works compare the quality of ANNs work, which have the same architecture, training parameters, volume and sample size, but are built using different methods, i.e. in different software development environments.

Often, the use of artificial neural networks on an industrial scale is associated with the use of expensive specialized software systems. These systems have an environment adapted for the implementation of ANNs and do not require users to have programming skills. A more affordable way to build and train a neural network from a financial point of view is to write your own software code using free interactive open source libraries. However, this method requires the user to have basic programming skills. The Scikit-learn library is open source, while the annual license for the STATISTICA software program costs about $25,000.

The aim of this work was to conduct a comparative analysis of the ANN quality in order to assess the technical condition of steel ropes by a combination of defective indicators built and trained by various methods, according to the criteria of test network performance, labor intensity and speed of network training, the average activation level of the "winning" neurons of the network and taking into account the financial costs of implementing and using the built artificial neural networks. In this regard, the task was set to create a new software tool for assessing the technical condition of steel ropes based on a combination of rejection criteria using two different types of ANNs: those built on the STATISTICA software package and those developed using the Scikit-learn interactive library.

Materials and Methods. The basis for ANNs training was the experience gained from operating steel ropes. This included a statistical database of typical damage to steel ropes and an expert assessment of their technical condition [9–12]. Figure 1 shows a neural network diagram that was used to assess the technical condition of a steel rope in all the methods described below.

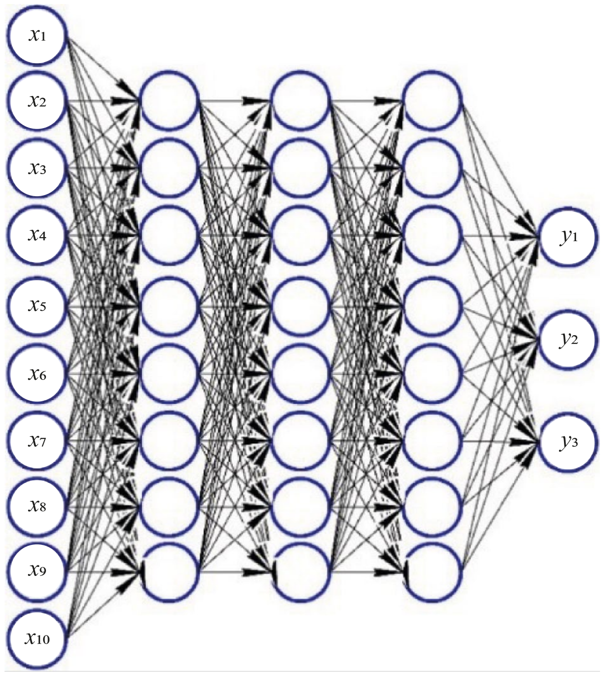

Fig. 1. ANN scheme for assessing the technical condition of a steel rope

Below are the parameters used in both methods of building the ANNs:

1. The so-called hyperparameters were set — parameters that did not change during network training. They included:

– 10 neurons of the input layer, equal to the number of defective parameters of the steel rope (x_1–x_{10});

– the number of output parameters (neurons), three possible states of the steel rope: 1 — operable, operation was allowed (y_1), 2 — defects within acceptable limits, operation was allowed with restrictions (y_2), 3 — the limit state had been reached, operation was prohibited (y_3);

– the number of intermediate layers, as well as the number of neurons in each intermediate layer.

Thus, the architecture of the neural network was defined [13].

2. The trainable parameters were set — parameters that were changed (optimized) in the process of network training: the values of synaptic weights *w* (the strength of the connection between neurons) and biases *b*. First, these values were set randomly, and then in the process of training the neural network, they were optimally configured.

3. The forward propagation algorithm was implemented by calculating a neural network based on randomly generated parameters *w* and *b*. To do this, training data was required, which consisted of samples of input parameters along with their corresponding known output parameters. These samples are shown in Table 1.

Table 1

Data for neural network training

No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	y
1	75	0	18	0	0	0	44	0	0	0	3
2	21	0	34	0	0	18	0	0	0	0	1
3	0	89	0	66	0	0	0	0	74	0	3
4	78	0	12	0	0	0	0	0	0	0	2
5	55	90	0	0	0	10	0	0	7	0	3
6	0	43	24	0	0	0	0	0	0	34	1
7	0	65	90	0	57	13	0	100	81	0	3
8	19	0	0	0	13	3	0	0	0	0	1
9	0	56	0	30	0	0	0	0	0	0	1
10	0	61	0	0	0	0	0	83	0	0	2
……	0	0	71	0	87	0	0	41	0	0	2
300	0	0	28	14	0	0	28	100	0	0	3

In Table 1, ten input parameters (x_1–x_{10}) represented the rejection values for steel ropes, expressed as a percentage of their limit values. This took into account a combination of various defects, which could be identified by expert means using a 3d model of the stress-strain state of the rope. Each combination corresponded to a specific technical condition of the rope. The volume of the training sample was 300 samples, while the control sample consisted of 30 samples. Ten test samples were also prepared for testing the ANN, but these were not included in the training process.

4. The activation function F was defined. This function was necessary to introduce non-linearity and a certain threshold value at the output of each neuron. We used the Relu activation function for this purpose. The formula below determined the level of neuron activation [14, 15]:

$$y = F\left(x_1 w_1 + x_2 w_2 + x_3 w_3 + b\right),$$

where y — level of neuron activation; x_1–x_3 — levels of activation of neurons of the previous layer; w_1–w_3 — synoptic weights; b — function offset.

Figure 2 shows a diagram of the formation of the activation level of one neuron.

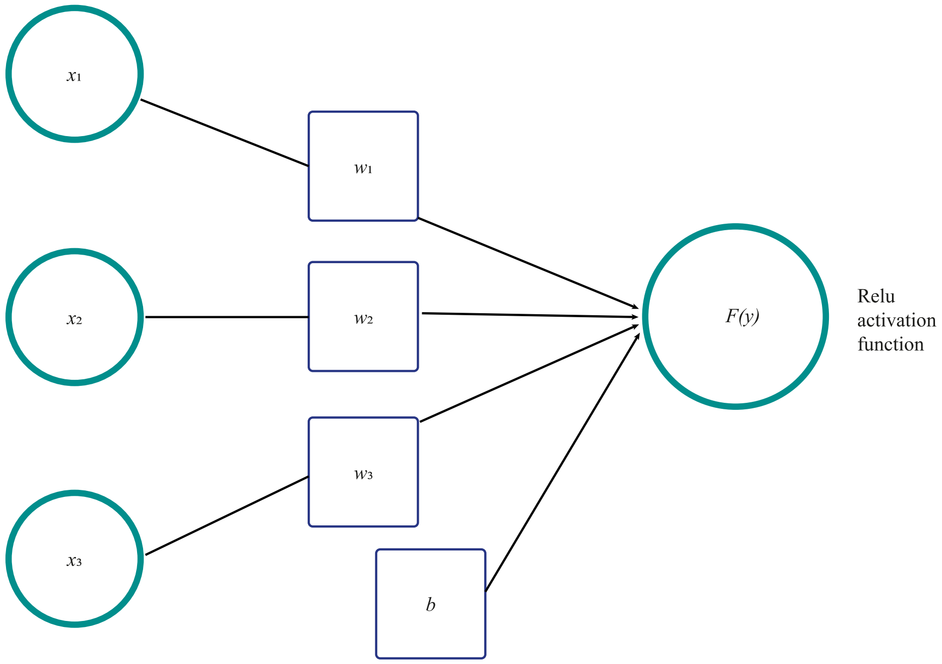

Fig. 2. Scheme of formation of the activation level of one neuron

5. A normalizing transformation of the activation values of the neurons in the last layer of the resulting network was performed using the softmax function, so that their values ranged from 0 to 1 and the sum of these values equaled 1. This transformation allowed for the interpretation of the activation levels of the neurons in a probabilistic sense. As a result, a prediction was made by the neural network — the state of the steel rope with a certain level of confidence for the current values of the synaptic weights (connections between neurons), w, and biases, b.

6. Calculation of error E between the calculated activation levels of neurons of output layer $y_{выч}$ and the target activation values of neurons of output layer $y_{цел}$ using the *MSE* (Euclidean distance) function or cross-entropy functions (used to determine the distance between probability distributions). It was important to remember that a neural network was trained with a teacher, which meant it used examples with known inputs and outputs. These examples were called training samples.

7. Implementation of the backpropagation algorithm, the purpose of which was to solve the problem of minimizing error function E depending on synaptic weights (connections between neurons) w and biases b. The gradient descent method was used for this purpose.

8. Repeating the entire learning algorithm on the next training sample (or group of samples) in order to minimize the error of the neural network by updating the connections (weights) between neurons. Each such repetition was called an epoch of learning. We set 2000 epochs of learning. The learning rate was 0.0001. The Adam error function. After completing a set number of training epochs, the neural network with all settings was saved and could be used to predict output parameters (the state of the steel rope) based on input parameters (combinations of defective indicators) that were not previously used in the network training process.

STATISTICA contains two built-in programming languages: STATISTICA BASIC and SCL (command language). The method of building a neural network in STATISTICA began with the launch of the “Neural Networks” module in the “Data Mining” tab on the main working panel of the program. The interface of the STATISTICA program practically did not differ from the well-known interface of the MS Office program. To build an ANN in STATISTICA, we set the network architecture and learning parameters specified in the above algorithm by pressing the appropriate keys using the adapted program interface.

The direct training of the neural network was activated by pressing the “Train” key in the STATISTICA working window, after which the ANN was checked on pre-determined control samples. The size of the control sample was 30. The condition for stopping the training process was when a benchmark network performance of at least 95% was achieved. The learning process of the neural network took about 20 seconds.

A step-by-step algorithm for writing the program code of a neural network using the interactive library Scikit-learn in the Python programming language was provided [4–7]:

1. In the first step, additional interactive libraries were installed. A library in this context meant a set of pre-written routines that made the programming process easier. To install a library, you need to enter the following code: (The explanations of the code or the commands being executed are provided in parentheses):

!python -m pip install pandas (data processing and analysis library);

!python -m pip install sklearn (machine learning library);

!python -m pip install openpyxl (library for working with Excel files).

2. In the second block, modules were imported by entering the following code:

import pandas as pd (data processing and analysis module);

from sklearn.neural_network import MLPClassifier (module for working with neural networks);

from sklearn.metrics import confusion_matrix, classification_report (additional module for working with neural networks);

import pickle (module used to save a trained neural network);

import joblib (module used to save a trained neural network).

3. Loading a database, i.e. a set of training data. It was necessary to prepare an Excel file with training data in advance, arranged in the format shown in Table 1 (a more simplified view is recommended — only columns of input and output parameters with their headers). To do this, we entered the following program code:

ds = pd.read_excel('book1.xlsx'), where book1.xlsx — an Excel file that should be located in the same folder as the file of the program being created;

ds.head(10) (code for visually displaying the first 10 rows of the table).

4. Next, values were assigned to the variables X and Y by writing the following program code:

X = ds.drop('Rope condition',axis=1) (all columns were assigned to variable X, except for column “Rope condition” (the literal name of the column was indicated);

y = ds['Rope condition'] (for variable Y, column “Rope condition” was assigned).

5. Building and training a neural network by writing the following code (this two-line program code replaced writing the neural network program code “manually” from the previous algorithm):

nn=MLPClassifier(hidden_layer_sizes=(8,8,8), max_iter=2000) (the architecture of the neural network was set, as well as the parameters of its training; in this case, 3 hidden layers, each with 8 neurons; the number of training epochs was 2000; by default, the Relu activation function was selected (code: activation='relu'), Adam error function (code: solver='adam'), learning rate 0.0001 (code: alpha=0.0001). It was possible to select various parameters of neural network training by writing the appropriate program codes separated by commas. All kinds of activation functions, error functions and other network parameters, their codes can be found on the official website of the interactive library Scikit-learn;

nn.fit(X, y) (introduction into the neural network of previously set parameters X — input variables (rejection indicators of steel ropes) and Y — output target variable (technical condition of steel ropes).

After launching this block, the neural network was built according to a given architecture and trained according to the specified learning parameters on training data (samples) uploaded via an Excel file table. The condition for stopping the training process was when a benchmark network performance of 95% was achieved. The learning process took approximately 1.5 minutes.

The following were the steps to save and use the ANN using the Scikit-learn interactive library:

1. Saving the trained neural network to a separate file by writing the following program code:

joblib_file = “joblib_model.pkl” (creating a joblib_model.pkl file);

joblib.dump(nn, joblib_file) (saving the nn neural network in the joblib_model.pkl file).

After running this block, the program created a joblib_model.pkl file in the same folder where the program file itself was located.

2. Creating a new file in PyCharm with py permission or in Jupyter with ipynb permission (the file in Jupyter was created for convenience, then the file would have to be saved in py format)).

3. Importing (to a new file) interactive libraries by writing the following program code:

import joblib (library for saving and embedding individual fragments of the program code);

import PySimpleGUI as sg (library for graphic design of the program).

4. Uploading a trained neural network to a new file via the joblib_model.pkl file, writing the following program code:

joblib_file = “D:\Python\PycharmProjects/joblib_model.pkl” (specifying the full path to the joblib_model.pkl file (individually for each user).

joblib_nn = joblib.load(joblib_file) (loading program code with a trained neural network).

5. Developing the graphical design of the program by writing the following program code:

```
sg.theme('DarkAmber')
layout = [ [sg.Text('Determination of the condition of the steel rope')];
[sg.Text('Enter 10 numbers separated by a space'), sg.InputText()];
[sg.Button('Ok'), sg.Button('Cancel')]
window = sg.Window('Window Title', layout)
while True:
event, values = window.read()
if event == sg.WIN_CLOSED or event == 'Cancel':
break
#Neural network
Xnew = [list(map(int, values[0].split()))]
y = joblib_nn.predict(Xnew)
#Popup window
if event == 'Ok':
window.disappear()
sg.popup('Rope condition ', y)
window.reappear()
print("Rope condition ', y)
window.close()
```

After starting this block, the program displayed the following working window (Fig. 3).

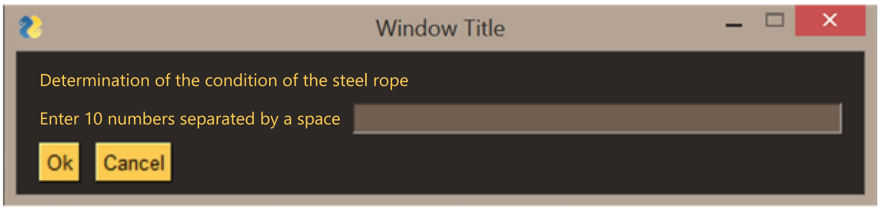

Fig. 3. Working window of the written program

In the working window of the program there was a line for entering 10 numbers separated by a space. In this line, the actual percentages of ten different defects of steel ropes from their permissible values were entered. After entering, for example, the following values [20 0 30 0 0 10 0 0 0 0] and pressing the “Ok” key, the program took the user to the next working window.

In the working window (Fig. 4), the program displayed the information message “Rope condition [1]”, which corresponded to the rope condition “serviceable, operation is allowed”.

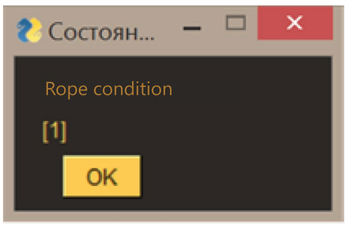

Fig. 4. Working window of the program with a determined rope condition

Results. Thus, two ANNs have been developed that have the same architecture, training parameters, composition, number and volume of training, control and test samples, but built using different methods. The results of work of the ANN, built in the STATISTICA software package, are presented in Table 2.

Table 2

Results of work of the ANN built in STATISTICA

Sampling (test)	Target	Network output	Rope condition-1 (confidence level)	Rope condition-2 (confidence level)	Rope condition-3 (confidence level)
1	1	1	0.64	0.18	0.18
2	2	2	0.15	0.73	0.12
3	2	2	0.24	0.69	0.15
4	3	3	0.03	0.28	0.69
5	3	3	0.15	0.21	0.64
6	1	1	0.55	0.31	0.14
7	3	3	0.03	0.21	0.76
8	1	1	0.68	0.21	0.11
9	2	2	0.26	0.61	0.13
10	2	2	0.14	0.53	0.33

The column “Rope condition — Target” shows the previously known state of the rope, in the column “Rope condition — Output” — the result of the neural network; subsequent columns indicate the confidence probabilities of determining a particular condition of the rope, which correspond to the activation levels of the output neurons of the network.

According to Table 2, it can be seen that the neural network correctly determined the condition of the steel rope according to the defective indicators in 10 out of 10 cases, i.e. the test performance was 100%. At the same time, the average value of the confidence levels for determining the condition of the ropes was 0.65.

The results of work of the ANN, built using the interactive library Scikit-learn, are presented in Table 3.

Table 3

Results of work of the ANN built using Scikit-learn

Sampling (test)	Target	Network output	Rope condition-1 (confidence level)	Rope condition-2 (confidence level)	Rope condition-3 (confidence level))
1	1	1	0.58	0.13	0.29
2	2	2	0.19	0.51	0.19
3	2	2	0.22	0.56	0.30
4	3	3	0.29	0.25	0.46
5	3	3	0.21	0.22	0.57
6	1	1	0.57	0.22	0.21
7	3	3	0.21	0.22	0.57
8	1	1	0.63	0.22	0.15
9	2	2	0.22	0.57	0.21
10	2	2	0.33	0.45	0.21

According to Table 3, it can be seen that the neural network correctly determined the condition of the steel rope according to the defective indicators in 10 out of 10 cases, i.e. the test performance was 100%. At the same time, the average value of the confidence levels for determining the condition of the ropes was 0.55.

Comparisons of test performance of neural networks with the same architecture and learning parameters, but built using different methods, showed that the ANN built on the basis of the STATISTICA software package and the ANN built using the Scikit-learn interactive library had a test performance of 100% with a test sample size of 10. However, the average confidence level (activation level of the “winning” neuron) for determining the state of the steel rope of the ANN built on the basis of the STATISTICA software package was 0.65, whereas the same indicator of the ANN built using the interactive library Scikit-learn was 0.55, which is 15% less.

Discussion and Conclusion. The results obtained showed that the ANN built using the STATISTICA software package, with the same architecture and network learning parameters, had more optimal software algorithms according to the criteria of confidence in assessing the technical condition of the steel rope and the speed of network learning, in comparison with the ANN built using the free Scikit-learn library. This can be explained by the fact that when developing algorithms for software complexes such as STATISTICA, specialized hardware complexes are used, including vector and tensor processors, which go far beyond the capabilities of the average application developer and require the involvement of highly qualified specialists. However, the indicator of the test performance of the ANN turned out to be the same for both ANNs. It is important to note that when evaluating this indicator, the test sample size was 10. If the test sample is increased, this indicator will be more accurate. At the same time, the achieved result justifies the use of TensorFlow, PyTorch, and Scikit-learn libraries by the world's leading research and commercial centers in the field of artificial intelligence.

In addition, the obtained scientific conclusion will allow us to numerically evaluate and compare the quality of ANNs having the same architecture and learning parameters, but built using different methods, and may be useful both for future scientific research in this field and for choosing the optimal environment for building ANNs in the industrial sphere. The developed programs can be used by specialists and experts as intelligent decision support systems for diagnosing the technical condition of steel ropes.

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Research Article

Diffusion Processes in the Formation of the Structure of Alloyed Powder Steels

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Abstract
Introduction. The production of alloyed powder steels continues to be one of the most promising areas in domestic powder metallurgy. This is due to the high level of performance characteristics and the wide range of products that can be produced. Creating materials with desired properties is a complex process that involves various phenomena. One of these phenomena is the diffusion alloying of iron-based powder steels, which plays a special role in this process. The creation of alloyed powder steels in the Fe-NiO and Fe-Ni systems is important for metallurgy and metalworking, as they are used for coating and sintering to obtain materials with specific properties. In addition, the diffusion of nickel in iron during heat treatment is considered to improve material properties. Recent advances in the study of mutual diffusion are associated with the investigation of homogeneous systems. However, mutual diffusion even in single crystals always occurs under spatially inhomogeneous conditions. The modern literature has not sufficiently studied the mutual diffusion in two- and multi-component powder systems. Therefore, the aim of this work is to determine the effect of diffusion alloying with nickel and nickel oxide of iron-based powder steel on the processes of obtaining powder materials. Within the framework of this goal, the following tasks were set: to investigate the diffusion processes of interactions between pairs in the Fe-NiO and Fe-Ni systems, as well as to study technological modes of sintering and reducing annealing of samples in order to achieve maximum mechanical properties that would ensure the formation of a high-quality product.
Materials and Methods. The work used iron powder of the PZHRV 2.200.26 brand manufactured by PJSC Severstal (Cherepovet) and carbonyl nickel powder PNK-UT3, obtained by the electrolytic method or splitting nickel salt with an aqueous solution, according to GOST 97922–97. Before use, the powders were tested using a universal laser particle size measuring device model FRITSCH ANALYSETTE 22 MicroTecplus and a Beckman COULTER No. 5 submicron particle analyzer. A two-cone mixer RT-NM05S (Taiwan) was used to prepare the charge. Pressing was carried out on a hydraulic press model TS0500–6 (China) in laboratory molds. Samples were obtained by pressing pre-hardened 3 mm diameter powder pins into a carbonyl nickel or NiO charge with a dispersion of 5–10 microns. Recovery annealing was carried out in a SNOL 6.7/1300 laboratory muffle furnace at 700°C, followed by annealing-sintering at temperatures of 1,050, 1,150 and 1,250°C in a hydrogen atmosphere for 9 hours.
Microstructural analysis was performed using a NEOPHOT-21 optical microscope. A Hitachi S-3400N scanning electron microscope was used to study the fine structure of the material. The distribution of element concentrations in the Fe-Ni diffusion zone was studied by local X-ray spectral analysis using the Kamebaks installation.
Results. The studies showed that the porosity of the powder component after pressing was 12%. Diffusion in the iron-nickel powder system was 5–10 times higher when using carbonyl nickel compared to oxide. It was also found that high diffusion rates of reduced nickel led to faster and more uniform penetration of alloying elements into the material. The dependences of the distribution of nickel concentration and its oxide content after sintering were

determined, as well as the indicators of diffusion interaction between iron, nickel, and nickel oxide during annealing, where nickel oxide was reduced and sintering occurred at different temperatures.
Discussion and Conclusion. The analysis of the results obtained indicates a different intensity of diffusion processes in powder-alloyed steels. This can be explained by both the distortion of the crystal lattice of the starting materials and the increased segregation of defects, such as defective zones, that are formed during compaction of the material. This approach to studying two-component diffusion allowed us to compare the intensity of element diffusion redistribution depending on chemical composition and temperature, and to estimate the effective activation energy of diffusion. As a result of our studies, we have established quantitative parameters for the distribution of nickel concentration in the iron matrix, depending on sintering temperature, which affects the formation of high-quality materials. The research results obtained are of interest to specialists in powder metallurgy and heat treatment, as they can be used in the development of new multicomponent alloys.

Keywords: powder steels, nickel oxide, nickel, diffusion, structure formation, sintering, splicing, contact section, mechanical properties

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Научная статья

Диффузионные процессы при формировании структуры легированных порошковых сталей

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Аннотация
Введение. Производство легированных порошковых сталей остается одним из перспективных направлений отечественной порошковой металлургии, что объясняется высоким уровнем эксплуатационных свойств и широкой номенклатурой получаемых изделий. Формирование таких материалов с требуемыми свойствами является сложным процессом, сопровождающимся многообразными явлениями, особое место среди которых занимает диффузионное легирование железной основы порошковых сталей. Создание легированных порошковых сталей в системе Fe-NiO и Fe-Ni имеет важное значение в металлургии и металлообработке при процессах нанесения покрытий и спекания для получения материалов с требуемыми свойствами. В процессе термической обработки для улучшения свойств материалов рассматривается и диффузионное взаимодействие никеля в железе. В последнее время успехи в изучении взаимной диффузии связаны с исследованием однородных систем. Однако взаимная диффузия даже в монокристаллах всегда протекает в пространственно-неоднородных условиях. В современной литературе недостаточно исследована взаимная диффузия в двух- и многокомпонентных порошковых системах. Поэтому целью работы является определение влияния диффузионного легирования никелем и оксидом никеля порошковой стали на основе железа на процессы получения порошковых материалов. В рамках обозначенной цели поставили задачи — исследовать диффузионные процессы взаимодействия пар в системе Fe-NiO и Fe-Ni, технологические режимы спекания и восстановительный отжиг образцов для достижения максимальных механических характеристик, которые бы обеспечивали формирование качественного материала.
Материалы и методы. В работе использовался железный порошок марки ПЖРВ 2.200.26 производства ПАО «Северсталь» (г. Череповец) и карбонильный порошок никелевый ПНК-УТ3 ГОСТ 97922–97, получаемый электролитическим методом или путем расщепления никелевой соли водным раствором. Перед использованием порошки проходили контроль на универсальном лазерном приборе измерения размера частиц модели FRITSCH ANALYSETTE 22 MicroTecplus и анализаторе субмикронных частиц Beckman COULTER №5.

Для приготовления шихты использовали двухконусный смеситель марки RT-NM05S (Тайвань). Прессование осуществлялось на гидравлическом прессе модели TS0500-6 (Китай) в лабораторных пресс-формах. Образцы получали запрессовкой заранее упрочненного порошкового штифта ø 3 мм в шихту карбонильного никеля или NiO с дисперсностью 5–10 мкм. Восстановительный отжиг образцов осуществляли в муфельной лабораторной печи SNOL 6,7/1300 при температуре 700 °C и отжиг-спекание при 1 050, 1 150, 1 250 °C в атмосфере водорода в течение 9 часов.

Фиксирование микроструктуры выполнялось на оптическом микроскопе «NEOPHOT-21». Тонкое строение структуры изучали на сканирующем электронном микроскопе Hitachi S-3400N. Распределение концентрации элементов в диффузионной зоне Fe-Ni изучали методом локального рентгеноспектрального анализа на установке «Камебакс».

Результаты исследования. Пористость порошкового компонента после прессования составляла 12 %. Диффузия в системе железо-порошок никеля, восстановленном из оксида, в 5–10 раз выше, чем при использовании порошка карбонильного никеля. Установлено, что высокая скорость диффузии восстановленного никеля приводит к более быстрому и равномерному проникновению легирующих элементов в материал. Определены зависимости распределения концентрации никеля и его оксида после спекания, а также рассчитаны показатели диффузионного взаимодействия между железом, никелем и оксидом никеля после операции отжига, при котором происходит восстановление оксида никеля и спекание при различных температурах.

Обсуждение и заключение. Анализ полученных результатов свидетельствует о различной интенсивности диффузионных процессов в порошковых легированных сталях. Объясняется это как искаженностью кристаллической решетки исходных материалов, так и увеличенной сегрегацией дефектов (содержанием дефектных зон), которые образуются в процессе уплотнения материала. Данный подход к исследованию двухкомпонентной диффузии позволил сопоставить интенсивности диффузионного перераспределения элементов в зависимости от химического состава и температуры, а также оценить эффективную энергию активации диффузии. В результате выполненных исследований установлены количественные параметры распределения концентрации Ni в железную основу в зависимости от температуры спекания, влияющие на формирование качественного материала. Полученные результаты исследований интересны специалистам в области порошковой металлургии и термической обработки при разработке новых многокомпонентных сплавов.

Ключевые слова: порошковые стали, оксид никеля, никель, диффузия, структрообразование, спекание, сращивание, контактное сечение, механические свойства

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Introduction. The performance characteristics of the material, both in its compact and powder forms, are primarily determined by its chemical composition and structural state [1, 2]. Depending on the purpose, specific requirements are imposed on the microstructure [3]. The formation of a specific structure of powder steel during sintering also depends on the processes that occur during sintering and subsequent heat treatment [4]. Many factors influence the process of structure formation in powder materials [5]. According to [6], the main factors are the methods of their production, granulometric composition, compacting pressure, sintering medium and time, temperature of deformation action. The introduction of alloying elements that affect the processes in the surface layers of particles during solid-phase sintering, and additives forming the liquid phase, is the most effective way to increase the level of operational properties [7]. Each of the factors has its advantages and disadvantages.

Powder alloyed steels have a high level of performance properties. They are characterized by a homogeneous structure and a homogeneous distribution of alloying elements throughout the steel structure [8]. When impregnated with liquid metals, for example, when using the cementation or carbonitration process, the alloying elements are absorbed by the surface layers of the material. This may lead to the formation of a surface layer with a high concentration of alloying elements, but deeper layers may be less saturated. Therefore, in such cases, impregnation with liquid metals is most effective for creating a surface layer with the desired properties [9]. Diffusion saturation can also lead to an uneven distribution of alloying elements. Diffusion can be limited only by surface layers of the material or internal defects, which limits the uniformity of saturation over the entire volume of the part. The choice of alloying method depends on the purpose, required properties, size and shape of the part, available resources and other factors. It is important to carefully consider all these factors when selecting a method to ensure optimal results.

The method of introducing nickel into powder structural steels in the form of additives of dispersed nickel oxides has proven itself well [10]. The recovery annealing of an iron-based charge with NiO particles evenly distributed in it leads to the recovery and fixation of the reduced nickel particles on iron particles by surface and grain boundary diffusion. The use of such a partially alloyed powder makes it possible to obtain parts with a homogeneous structure and a high complex of mechanical properties at a lower temperature. Activation of homogenization process of powder steels using oxides of alloying elements in the literature is explained only at a qualitative level [11]. Therefore, the aim of this work was to study the processes of diffusion interaction in Fe-Ni and Fe-NiO systems to determine the quantitative parameters of diffusion in them. The main task within the framework of this goal was to study the influence of technological modes of sintering and diffusion annealing during diffusion interaction in a system of Fe-Ni and Fe-NiO pairs on the formation of high-quality powder steel.

Materials and Methods. In the work, powder PZHRV 2.200.26, produced by Severstal PJSC (Cherepovets) and nickel carbonyl powder PNK-UT3 GOST 97922-97, obtained by electrolytic method or by splitting nickel salt with an aqueous solution, were used [12]. Data on the total chemical composition are presented in Table 1.

Table 1

Chemical composition of PZHRV 2.200.26 powder

Powder grade	Mass content of components, %									
	Mo	Ni	C	O	H	Cu	Si	Mn	P	S
PZHRV 2.200.26	–	–	0.090	0.140	–	–	0.014	0.087	0.012	0.005

Technological properties of PZHRV 2.200.26 powder: bulk density — from 2.4 to 3.0 g/cm^3; fluidity — no more than 37 sec/50 g; density at P=700 MPa — 7.0–7.05 g/cm^3; strength at a density of 6.5 g/cm^3 — more than 14 N/mm^2. The analog is powders from the Swedish company Höganäs: AHC 100.29, NC 100.24, SC 100.26, ASC100.29. Scope of application: shock absorption group parts, transmission parts, body parts, gears, connecting rods, couplings, bushings, etc. Main qualities of PNK-UT3 nickel powder include high corrosion resistance and resistance to aggressive environments.

Powder compositions are characterized by a high intensity of boundary and surface processes, which, during diffusion, can lead to an intensification of mass transfer [13]. The regularity of the structure formation of powder materials has been studied. The processes of diffusion interaction of alloying components were modeled using the diffusion pair method [14].

Granulometric composition of PZHRV 2.200.26 iron powder was determined using a universal laser particle size measuring device of a FRITSCH ANALYSETTE 22 MicroTecplus model (Germany) and a Beckman COULTER submicron particle analyzer No. 5 (USA).

Diffusion processes were considered on model pairs of powders of the grades PZHRV 2.200.26 (powder) — Ni (carbonyl); PZHRV 2.200.26 (powder) – NiO, which were manufactured by pressing a rod from the PZHRV 2.200.26 material with a diameter of 3 mm into a powder of carbonyl Ni or NiO with a dispersion of 5–10 microns. Recovery annealing of steam samples was performed at a temperature of 700°C and annealing-sintering at 1,050°C, 1,150°C, and 1,250°C in a hydrogen atmosphere for 9 hours [15].

Fe-Ni pair refers to systems with unlimited solubility of components. Iron and nickel at the temperature of diffusion annealing possess FCC lattices with similar parameters and form solid substitution solutions. Upon cooling, iron alloys containing less than 6% of nickel recrystallize into a ferritic phase with a BCC lattice. Metallographic studies were carried out after annealing with preliminary preparation of the sections in a plane perpendicular to the initial boundary between the components of the pair.

The distribution of concentration of elements in the Fe-Ni diffusion zone was studied by local X-ray spectral analysis at a Camebax installation manufactured by Cameca (France). The survey was carried out in the plane of the section in the direction perpendicular to the initial boundary between the components of the pair (along the axis of the primary cylindrical iron sample). Four concentration curves of distribution of relative intensities of $K_{\alpha 1}$ line of iron and nickel were recorded from each section along the cross section of the diffusion zone in increments of 1 μm. The nickel and iron contents were determined at each point of the concentration curve under study. The formation of the diffusion zone increased 1.6–2.2 times due to the presence of nickel oxide paired with iron compared to pure nickel [16]. The coefficients of mutual diffusion $\overline{D}$ during sintering in the ranges of 1,050°C–1,250°C were determined depending on the content of alloying elements [17, 18].

Microstructure was fixed using an optical microscope “NEOPHOT–21” by Carl Zeiss Jena (Germany). The fine structure of the sample was studied using a Hitachi S-3400N scanning electron microscope (Taiwan).

The calculations were performed using mathematical methods based on the Matano method [16].

Results. The porosity of the powder component after pressing was 12%. Granulometric composition of PZHRV 2.200.26 iron powder was determined on the histogram: there was a single peak indicating that the powder was monofractive (Fig. 1). The average particle size was 98.5 microns. The results are presented in Table 2.

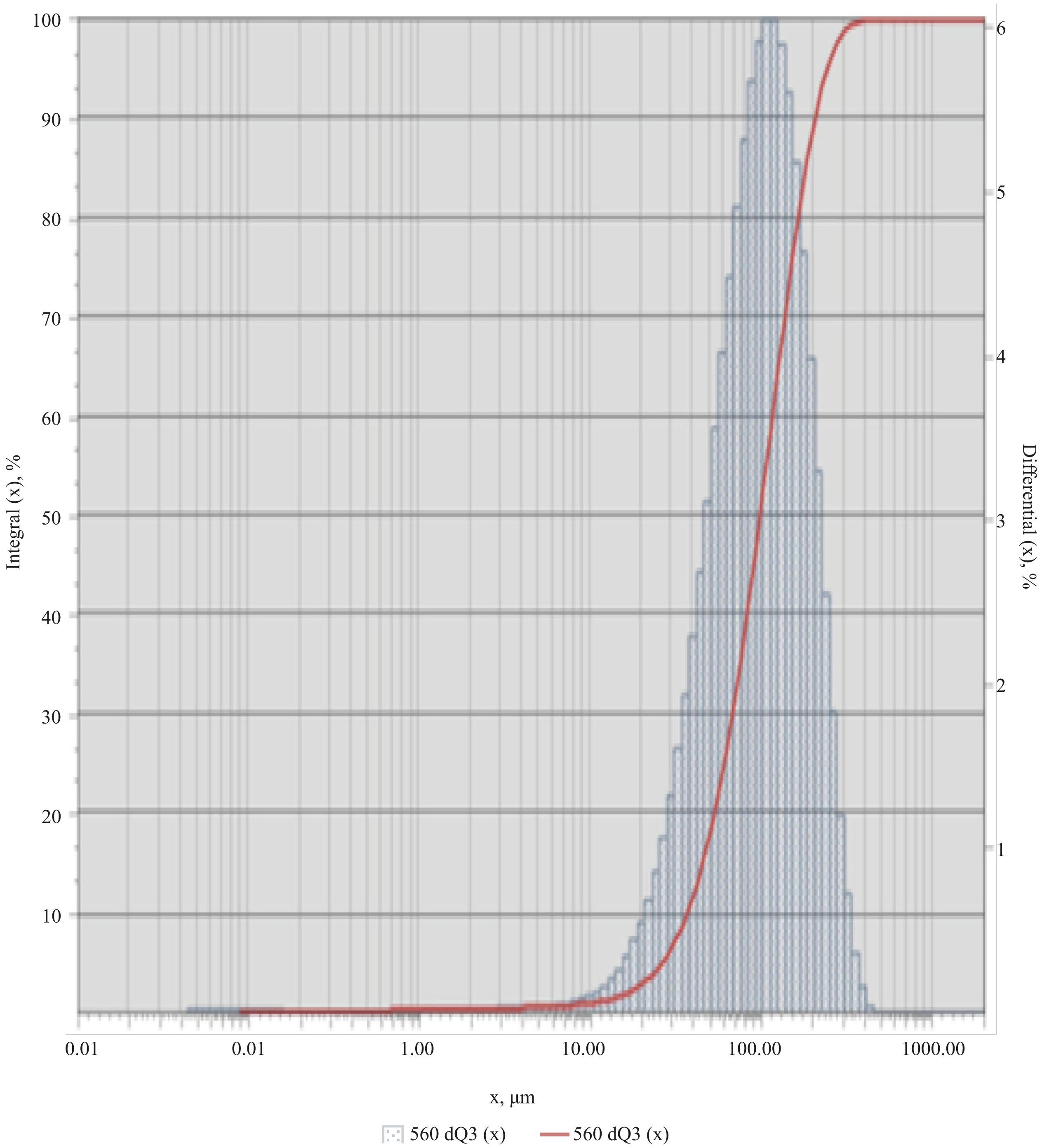

Fig. 1. Granulometric composition of PZHRV 2.200.26 iron powder

Table 2

Granulometric composition of PZHRV 2.200.26 iron powder

Quantitative share, %	5	10	25	50	75	90	95	99
Dimension, microns	26.5	37.0	60.7	98.5	149.8	206.4	244.0	317.4

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Figures 2 *a* and *b* present a general view of the iron powder of the PZHRV 2.200.28 grade. Figures 2 *c, d, e, f, g, h* show the morphology of iron powder particles obtained using a Hitachi S-3400N scanning electron microscope.

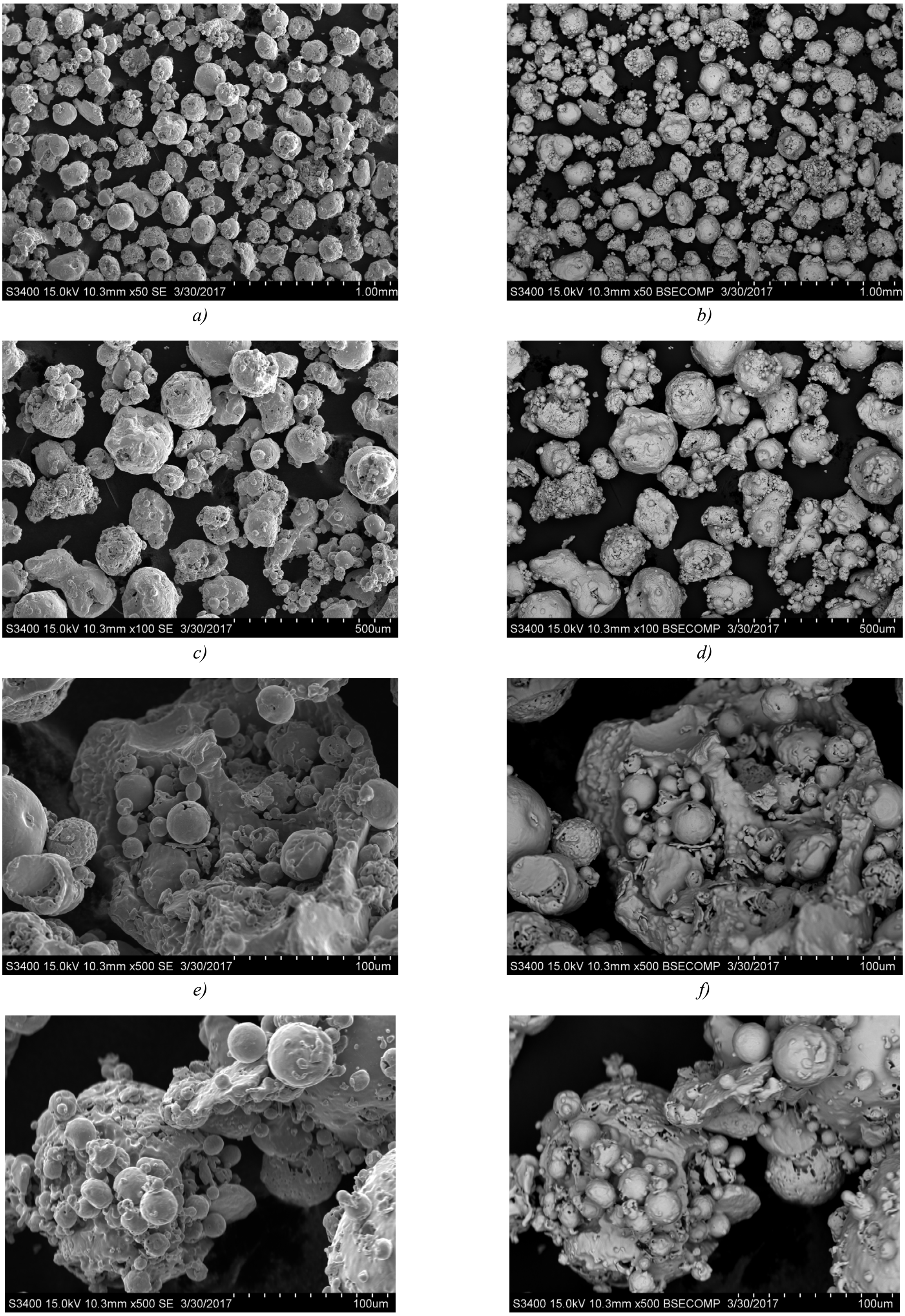
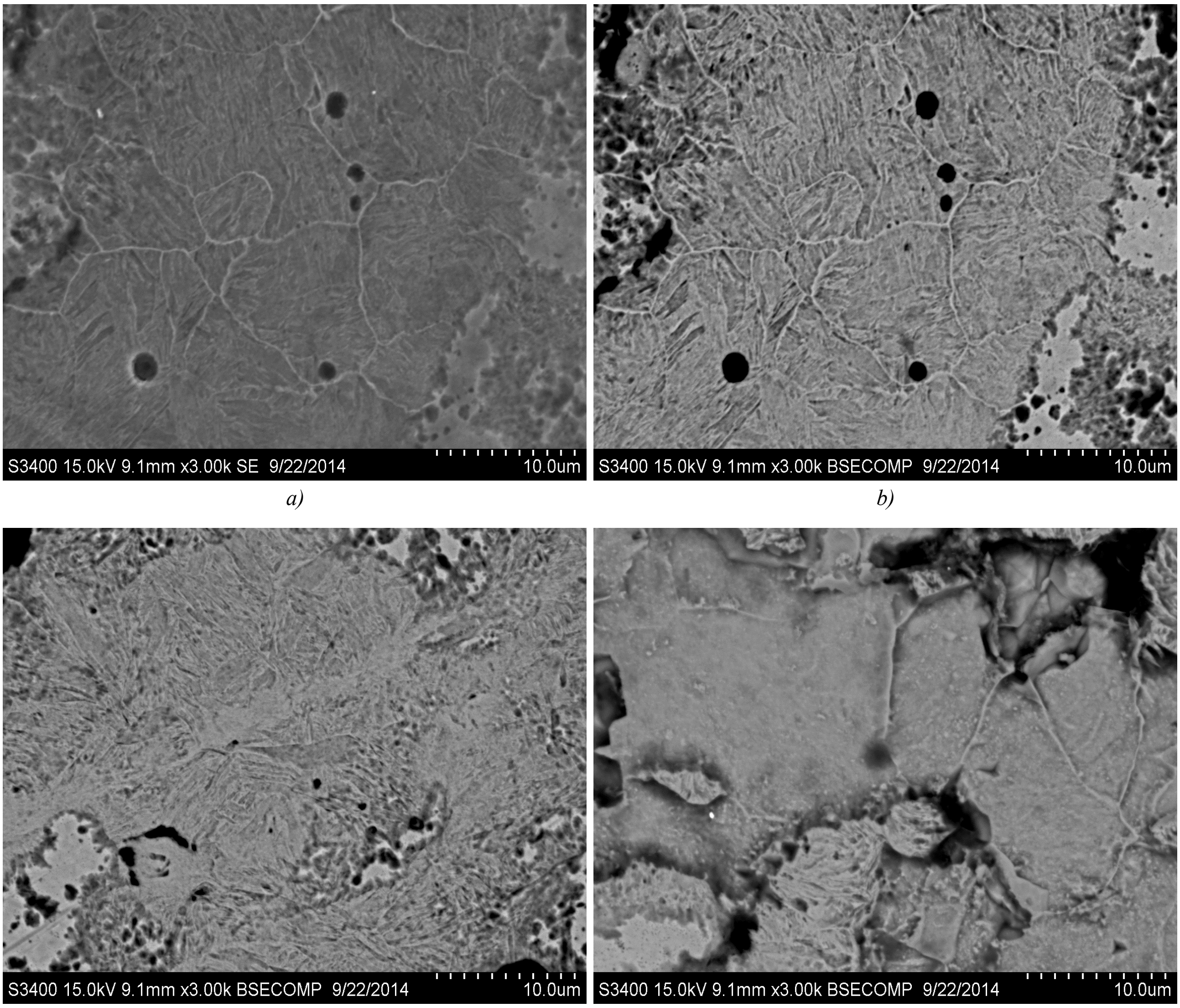


Fig. 2. SEM image of PZHRV 2.200.28 iron powder shooting in:
a, c, e, g — reflected electrons; *b, d, f, h* — in secondary electrons

The structure of the diffusion zones consisted of ferritic and austenitic phases separated by a boundary. At a sintering temperature of 1,050°C, a porous austenitic phase was observed (especially in samples containing NiO oxide), due to high negative volumetric effects during the recovery of NiO. Sintering led to more intensive compaction when the temperature rose to 1,150°C and 1,250°C. Intensification was observed in samples reduced from Ni oxide. A significant increase in the volumetric fluidity of the material after the recovery of nickel oxide particles was explained by increased structural unevenness and incorrect arrangement of dislocations, in comparison with the structure of a powder material with nickel particles. The latter were characterized by a uniform arrangement of dislocations, which were less susceptible to annihilation during pre-annealing. The recovery of nickel oxide was accompanied by movement of the interparticle surface of the fusion, which led to the formation of a defective structure. In the process of NiO recovery, a complicated structure was formed in the volume of the migrating NiO-Ni boundary due to disoriented dislocations that did not disappear even at high sintering temperatures (Fig. 3).



a) *b)*

c) *d)*

Fig. 3. Microstructures of an alloy made of PZHRV 2.200.26 powder when Ni was introduced into the initial charge in the amount of: *a, b* — 20%; *c, d* — 40% at a sintering temperature of 1,150°C

The diffusion of nickel into powdered iron was most active along grain boundaries with a deviation deep into the grain. This was due to the lower activation energy of the grain boundary diffusion process compared to the bulk one. The high diffusion permeability of grain boundaries was due to their defective structure. The predominant dissolution of nickel along the boundaries of iron grains was more pronounced at a low sintering temperature (1,050°C), when volumetric diffusion was difficult (Fig. 4, 5).

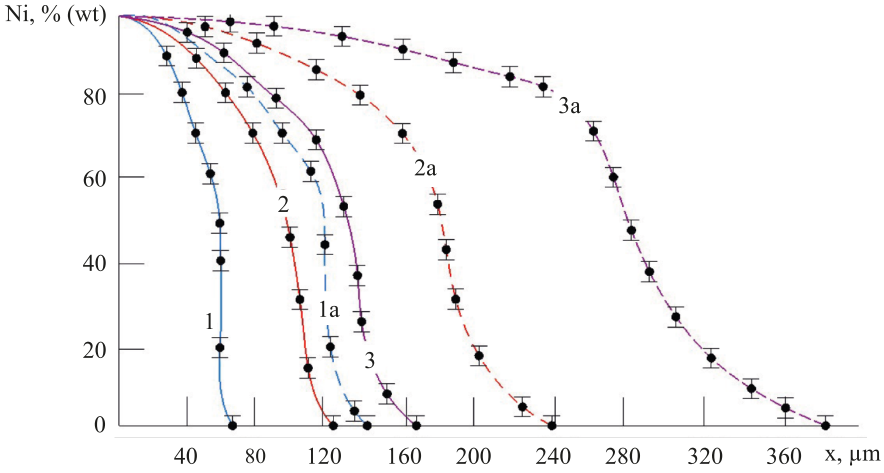


Fig. 4. Distribution of Ni concentration in the diffusion zone of Fe-Ni pairs (solid line 1, 2, 3) and Fe-NiO (dotted line 1 *a*, 2 *a*, 3 *a*) after sintering in a hydrogen atmosphere at temperatures:
1, 1 *a* — 1,050°C; 2, 2 *a* — 1,150°C; 3, 3 *a* — 1,250°C

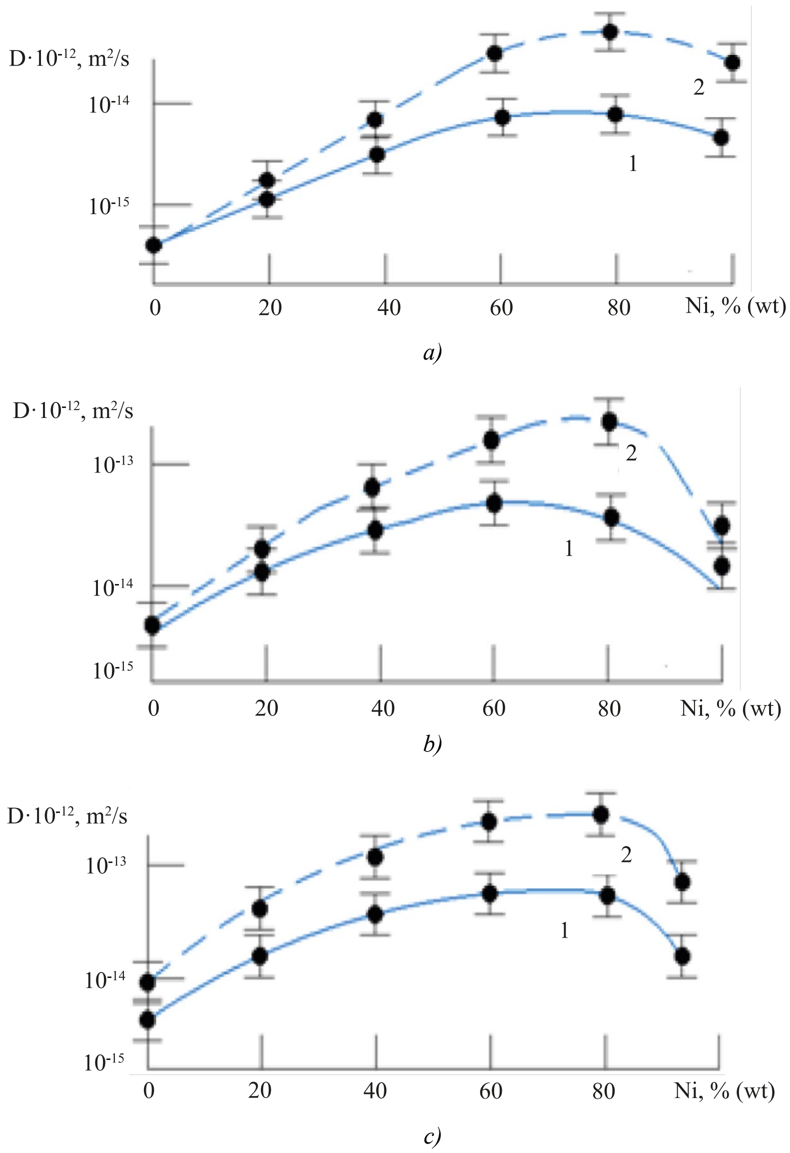


Fig. 5. Dependencies of the coefficients of mutual diffusion of Fe-Ni (line 1 and Fe-Ni (line 2) after annealing and sintering at temperatures:
a — 1,050°C; *b* — 1,150°C; *c* — 1,250°C

On all curves, the mutual diffusion coefficient had a maximum at a nickel concentration of more than 60%. These data coincided with the results of the work in which the coefficients of mutual diffusion were analyzed by finite element modeling of a simple model. At sintering temperatures of 1,050°C and 1,150°C in this concentration range, the mutual diffusion coefficient in the Fe-NiO pair was about 10 times higher than in the Fe-Ni pair [19]. With an increase in the sintering temperature to 1,250°C, this difference existed throughout the concentration range, which was also confirmed by the results of [18] and was shown in Figure 6.

Active diffusion energy $\overline{E}$ and pre-exponential multiplier $\overline{D_0}$ were determined based on the temperature dependencies of the mutual diffusion coefficients in accordance with the Arrhenius formula [6]:

$$\overline{D} = \overline{D_0}\, exp - \frac{\overline{E}}{RT} \qquad (1)$$

The diffusion energy in all the cases considered was found to be lower than the values reported in the literature for compact materials [19].

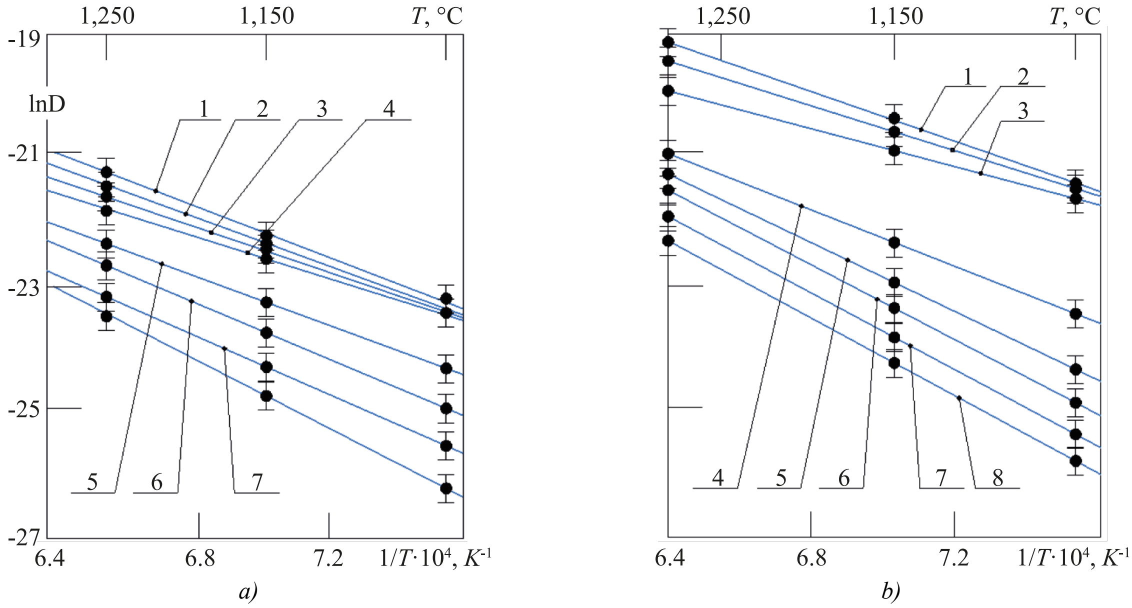


Fig. 6. Temperature dependencies of mutual diffusion coefficients:
a — Fe-Ni systems; *b* — Fe-Ni systems on NiO concentration:
1 — 90%; 2 — 80%; 3 — 70%; 4 — 50%;
5 — 40%; 6 — 30%; 7 — 20%; 8 — 10%

The porosity and structural activity of the nickel powder component influenced the increase in the processes of surface and grain boundary diffusion, which were realized by mechanisms with low activation energies, as well as diffusion by defects. The activation energy (Fig. 7) and the pre-exponential multiplier had a minimum in the concentration range of 50–70% Ni (Fig. 8). $\overline{E}$ values were suitable for Fe-NiO and NiO systems. Pre-exponential multiplier $\overline{D_0}$ in the Fe-NiO system was significantly greater than in the iron-nickel system, and increased the coefficient of mutual diffusion of elements during recovery annealing and sintering. Under thermomechanical action, as well as during the diffusion of carbon into the iron crystal lattice, the interparticle surface of the fusion was displaced, which could serve as the beginning of crack development [19]. This was due to an increased defect in the nickel structure after recovery, which was confirmed by X-ray analysis data [19]. The dislocation density of nickel powder recovered from oxide at a temperature of 700°C was 1.8·1,010. For carbonyl nickel it was $1.0 \cdot 10^8$ cm^{-2}.

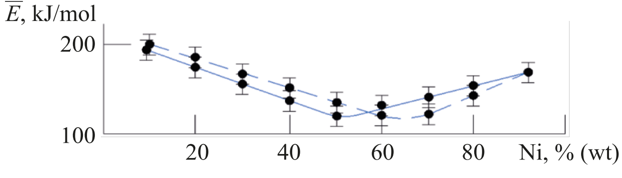


Fig. 7. Activation energy of mutual diffusion $\overline{E}$ in Fe-Ni systems (dotted line) and Fe-NiO systems (solid line)

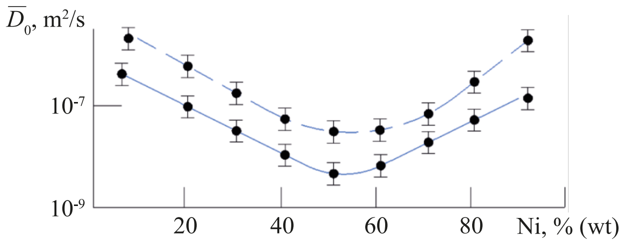


Fig. 8. Pre-exponential multiplier $\overline{D_0}$ (m²/s) in Fe-Ni (dotted line) and Fe-Ni (solid line) systems

Discussion and Conclusion. The process of diffusion annealing of samples obtained from PZHRV 2.200.26 iron powder is accompanied by the so-called "Frenkel effect", when atoms, ions or defects in a crystalline material can move or diffuse at elevated temperatures. During diffusion annealing, diffusion and recombination of defects such as vacancies (absence of an atom in the crystal lattice) and vacancy defects (atoms in the wrong places in the crystal lattice) are possible. As a result, the crystal can transform or get rid of these defects. When a vacancy and a vacancy defect are in close proximity, a Frenkel pair is formed. These pairs can move through the crystal via diffusion. If a Frenkel pair comes into contact with one of the vacancies, it can eliminate two defects and thereby purify the crystal of defects.

During the sintering process of alloyed powder steel, atoms diffuse between the powder particles, forming bonds at the interface. The diffusion of alloying elements in the powder steel leads to the formation of intermetallic compounds, as well as the creation of dispersed and basic phases. These diffusion processes can be accelerated by increasing the sintering temperature.

As a result of the studies performed, the quantitative parameters of Ni concentration distribution in the iron base were determined depending on the sintering temperature. The minimum distance over which nickel is distributed is 70 microns at a sintering temperature of 1,050°C. When sintered at 1,250°C, the distribution zone of pure nickel increases to 165 microns. However, when using nickel oxide, this zone increases above 360 microns at the same temperature. This indicates that the diffusion in a system with nickel powder recovered from oxide is 5–10 times higher than when carbonyl nickel powder is used. This may be important in the processes of alloying or saturating materials. The high rate of diffusion of recovered nickel can lead to faster and more uniform penetration of alloying elements into the material. This can be useful when creating a surface layer with certain properties or increasing the strength and other mechanical properties of the material.

The analysis of the results obtained indicates a different intensity of diffusion processes in powder alloyed steels. This is associated not only with the distortion of the crystal lattice of the starting materials, but also with an increased concentration of defects formed during the pressing of blanks. An understanding of diffusion processes and their influence on the formation of the structure of alloyed powder steels makes it possible to optimize sintering processes and obtain materials with desired properties and microstructure. Thus, the choice between nickel powder recovered from oxide and carbonyl nickel powder should be based on specific requirements and process conditions. Further research and experimentation can help to fully explore the potential of these options and determine the most effective approach for a given application.

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RV Egorova: academic advising, analysis of the research results, revision of the text, correction of the conclusions;

ZhV Eremeeva: preparation of samples for research on a scanning microscope, analysis of microstructure results and construction of mathematical dependencies.

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Research Article

Destruction of Internal Anticorrosive Polymer Coatings of Oilfield Pipes during Operation

EDN: CHUJHA

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Abstract

Introduction. Failure of equipment, specifically pipes in the oilfield complex, due to the development of corrosion processes leads to numerous losses, destruction of expensive components, disruption of technological processes and, as a result, environmental damage. The use of anticorrosive coatings as an internal protection of oilfield pipes offers many advantages and can significantly reduce the rate of corrosion, but does not provide a complete solution to this problem. Destruction of internal anticorrosive polymer coatings (IACPC) occurs for numerous reasons. The causes and mechanisms of destruction are insufficiently investigated. Therefore, the aim of this work was to analyze the destruction of internal anticorrosive polymer coatings using practical examples, which made it possible to form and identify the main causes of damage and degradation of coatings during operation.

Materials and Methods. A complex of laboratory studies was carried out to study the damage to internal polymer anticorrosive coatings during operation and to establish the main causes of destruction. The initial phase of the investigation involved a detailed examination of the materials related to the accident circumstances, including the operating conditions of the coated pipeline (composition of the operating medium, temperature, pressure, and presence of mechanical impurities), operation time, and type of polymeric material used. The second phase involved laboratory testing of the coating, which included the determination of layer thickness, dielectric continuity, adhesive strength (by the normal separation method), investigation of thermokinetic properties by means of differential scanning callometry (DSC), study of the coating structure using scanning electron microscopy.

Results. Practical examples of the destruction of internal anticorrosive coatings of oilfield pipes were analyzed. For each case, characteristic signs of degradation of the anti-corrosive coating were identified. Changes in the microstructure of the coatings, as well as the formation of corrosion products, were observed depending on the type of destruction. The focus was on studying the degree of polymerization of the coating, both using the traditional method of determining the ΔTg parameter using DSC, and based on indirect signs detected during microscopic studies.

Discussion and Conclusion. The practical cases of damage to the internal anticorrosion coating of pipes of the oil and gas complex considered in the article allowed us to divide the causes of destruction into three groups: operational, technological and defects during transportation, storage and construction and installation works. Based on these findings, we have formulated recommendations for manufacturers to ensure maximum performance from their coatings. It is noted that the compliance with the presented recommendations makes it possible to obtain internal anticorrosive polymer coatings with a minimum guaranteed lifespan of 15 years, as demonstrated by the successful operations of pipelines in Western Siberia, such as those operated by Surgutneftegaz PJSC and LUKOIL – Western Siberia LLC.

Keywords: internal anticorrosive polymer coating, destruction of the coating, adhesive strength, operational defects, peeling of the coating, corrosion products, cracking, blistering

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Научная статья

Разрушение внутренних антикоррозионных полимерных покрытий нефтепромысловых труб при эксплуатации

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Аннотация

Введение. Отказ оборудования — труб нефтепромыслового комплекса — по причине развития коррозионных процессов приводит к многочисленным убыткам, разрушению дорогостоящих комплектующих, нарушению работы технологических процессов и, как следствие, экологическому ущербу. Применение антикоррозионных покрытий в качестве внутренней защиты нефтепромысловых труб имеет много преимуществ и позволяет значительно снизить скорость коррозии, но не обеспечивает полного решения данной проблемы. По многочисленным причинам происходят разрушения внутренних антикоррозионных полимерных покрытий (ВАКПП). Недостаточно исследованными являются причины и механизмы разрушения. Поэтому целью данной работы стало проведение анализа разрушений внутренних антикоррозионных полимерных покрытий на практических примерах, что позволило сформировать и выделить основные причины повреждения и деградации покрытий при эксплуатации.

Материалы и методы. Для изучения повреждений внутренних полимерных антикоррозионных покрытий в процессе эксплуатации и установления основных причин разрушения проводился комплекс лабораторных исследований. Первоначальным этапом исследования являлось подробное изучение материалов обстоятельства аварии: условия эксплуатации трубы с покрытием (состав эксплуатируемой среды, температура, давление, наличие механических примесей), наработка, тип применяемого полимерного материала. Второй этап — лабораторные исследования покрытия: определение толщины слоя, диэлектрической сплошности, адгезионной прочности (методом нормального отрыва), исследование термокинетических свойств посредством дифференциально-сканирующей каллометрии (ДСК), изучение структуры покрытия при помощи сканирующей электронной микроскопии.

Результаты исследования. Изучены практические примеры разрушения внутренних антикоррозионных покрытий нефтепромысловых труб. Для каждого исследуемого случая выявлены характерные признаки деградации антикоррозионного покрытия. Показаны изменения микроструктуры покрытий, а также образование продуктов коррозии в зависимости от характера разрушения. Делается акцент на исследовании степени полимеризации покрытия как с помощью традиционного метода определения параметра ΔTg с помощью ДСК, так и на основе косвенных признаков, обнаруженных в ходе микроструктурных исследований.

Обсуждение и заключение. Рассмотренные в статье практические случаи повреждения внутреннего антикоррозийного покрытия труб нефтегазового комплекса позволили разделить причины разрушения на три группы: эксплуатационные, технологические и дефекты в ходе транспортировки, хранения и строительно-монтажных работ. Сформулированы рекомендации производителям, позволяющие получать покрытия с максимальными характеристиками, присущими используемому лакокрасочному материалу. Отмечено, что соблюдение представленных рекомендаций позволяет получать в условиях Западной Сибири внутренние антикоррозионные полимерные покрытия с гарантированным ресурсом не менее 15 лет (что подтверждается опытом успешной эксплуатации таких трубопроводов в ПАО «Сургутнефтегаз» и ООО «ЛУКОЙЛ – Западная Сибирь»).

Ключевые слова: внутреннее антикоррозионное полимерное покрытие, разрушение покрытия, адгезионная прочность, эксплуатационные дефекты, отслоение покрытия, продукты коррозии, растрескивания, вздутия

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Introduction. Failures of oilfield pipelines due to internal corrosion cause significant losses [1]. The main damage is caused by the destruction of essential components, leading to disruption of operational processes and high levels of economic and environmental harm [2]. To address this issue, various methods for protecting the inner surfaces of pipes have been developed. These include the use of corrosion inhibitors, corrosion-resistant steels, non-metallic materials, and internal anticorrosive coatings [3]. All these methods aim to reduce the rate of corrosion under specific operating conditions [4]. The most promising method to protect metal from corrosion is the use of anticorrosive polymer coatings, which prevent the impact of aggressive components of the transported medium on the inner surface of the pipe [5]. As a result, the destruction of metal caused by corrosion is significantly reduced, ensuring long-term, trouble-free operation of equipment [6]. Liquid and powder-based polymer coatings are two of the most reliable and versatile methods of protecting the inner surfaces of oilfield pipes [7]. Powder coatings based on epoxy resins are preferred due to their excellent performance and durability [8].

One of the main advantages of using anticorrosive polymer coatings is the possibility to use materials that are relatively inexpensive instead of more expensive options. For example, carbon steel pipes with a corrosion-resistant coating can be used instead of high-alloy steel pipes. In addition, due to the low roughness of the polymer coating, the flow rate of pipes increases [9], the formation of salt [10], asphalt-resinous and paraffin deposits decreases significantly [11]. Compared to the chemical method of protecting pipes (through the use of corrosion inhibitors), internal polymer-based coatings have several advantages. These include:

1. Internal anticorrosive polymer coatings are more effective, as they form a physical barrier between the aggressive environment and the metal. Inhibitors affect the corrosion process only in direct contact with the metal surface.

2. Polymer coatings have a longer service life, while the action of the inhibitor may cease when its concentration in solution is depleted.

3. In compliance with the technical regulations, anticorrosive coatings are easily applied to the inner surface of the metal. When using corrosion inhibitors, it is necessary to carefully calculate the concentration and method of introducing them into the working environment.

Given that corrosion inhibitors are acidic chemical solutions, their use can adversely affect the properties of tubing materials. When an inhibitor comes in contact with a metal surface of a pipe, as well as when it penetrates a threaded connection of a "tubing nipple – coupling", metal destruction through the mechanism of hydrogen cracking may occur [12].

Nevertheless, polymer anticorrosive coatings also have a number of disadvantages, which include: aging of the polymer base, diffusion of the transported medium through the coating, and relatively low impact strength [5].

The effectiveness and durability of an anticorrosive coating depend on a variety of factors that influence its protective ability. One of the most significant indicators of a coating's quality is the adhesion strength between the polymer and the metal substrate, which depends on the application technology. The quality of the materials used, compliance with correct preparation techniques for the metal surface, and the coloring process play a crucial role in determining the adhesive strength. Additionally, temperature drying conditions are essential [13]. Along with the above requirements, the stability of the protective properties of the polymer coating does not always depend on the coating itself, but is also determined by the operating conditions and parameters [9]. The main technological factors contributing to the IACPC degradation and premature destruction can include: disruption of well operation due to a sharp drop in the temperature of the pumped product or pumping of the product at a temperature higher than the design temperature; excess pressure; the presence of high corrosion activity of the extracted products; incorrectly selected type of coating for specific operating conditions.

There are frequent cases of damage to the polymer coating during scraping (cleaning) of the borehole from the formed asphalt-resin-paraffin deposits. The use of an improperly designed scraper contributes to the violation of the integrity of the surface layer of the coating. Scratches and protruding burrs are formed, which reduce the barrier properties of the polymer coating during further operation.

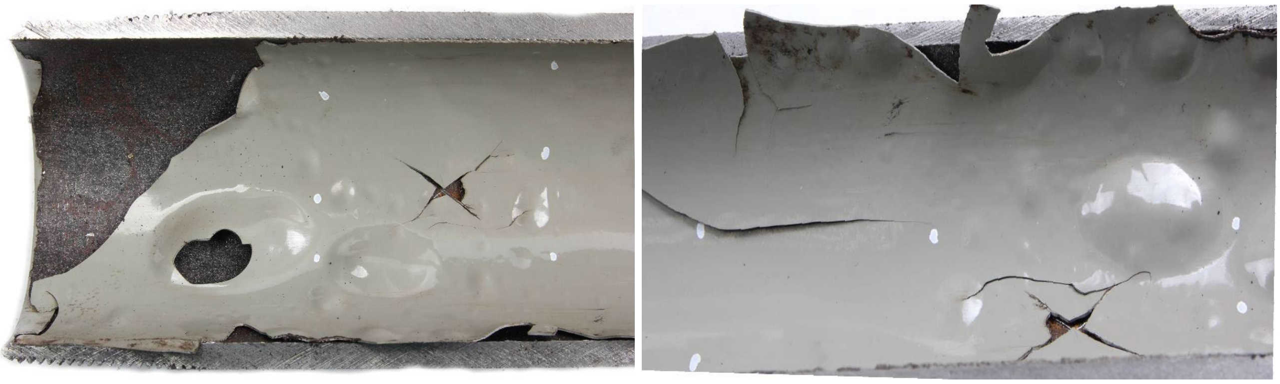
The existing literature [14] on the issues of internal protection of oilfield equipment using polymer coatings only considers a small part of the problem and does not reflect the full picture of the IACPC destruction. It is important to note that depending on changing factors such as operating conditions, the type of polymer material used, technological operations of preparation and coating, the destruction of the anticorrosive coating may have a different character. Thus, due to the complexity of the kinetics of the coating destruction process and the lack of a practical basis, it is not always reliably possible to determine the true cause of coating damage. Numerous studies conducted by the authors on oilfield pipes allowed us to consider some new specific examples of IACPC destruction during operation and identify the main causes leading to degradation and failure of internal anticorrosive coatings, taking into account new factors.

Materials and Methods. The following samples with damage to the internal anticorrosive coating were selected as samples for the study:

1. A fragment of tubing Ø73×5.5 mm with damage to the coating in the form of blisters along the entire length of the sample. The tubing failed after 934 days of operation (Fig. 1 *a, b*).
2. A fragment of tubing Ø73×5.5 mm with the destruction of the coating in the form of extensive areas with detachments and blisters localized mainly in the nipple part of the tubing. The time to failure was 146 days (Fig. 2 *a, b*).
3. A fragment of tubing Ø73×5.5 mm with a different color of the inner coating (Fig. 3 *a, b*).
4. A fragment of the pipeline Ø325×8 mm, with the coating destroyed, exposing the metal substrate, and a through defect in the pipe (Fig. 4 *a, b*).
5. A fragment of the pipeline Ø159×8 mm with the formation of numerous blisters of the coating and its destruction (Fig. 5).

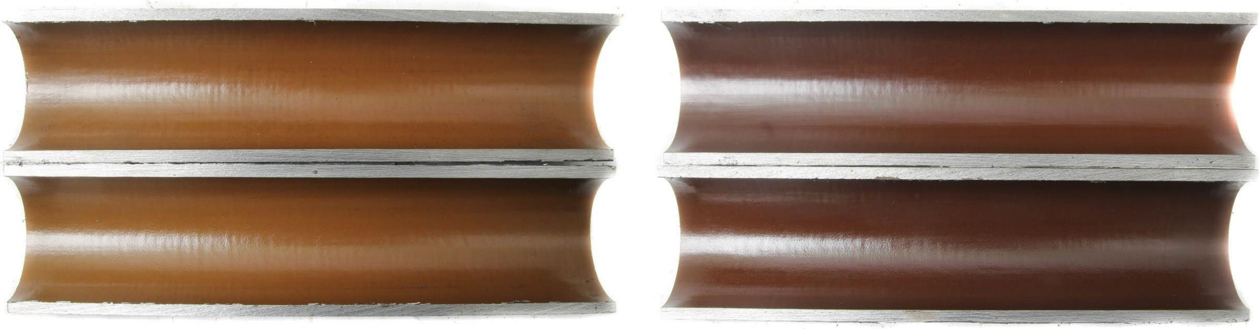
a) *b)*

Fig. 1. Damage to the internal anticorrosive coating:
a, b — coating blistering



a) *b)*

Fig. 2. Destruction of the internal anticorrosive polymer coating:
a — blistering of the coating; *b* — cracking of the coating



a) *b)*

Fig. 3. Different shades of the internal anticorrosive coating of the tubing:
a — light brown shade of the coating; *b* — dark brown shade of the coating

a)

b)

Fig. 4. Damage to the internal anticorrosive coating of the pipeline Ø325×8 mm:
a — general view of the destruction of the coating; *b* — burns of the coating

Fig. 5. Destruction of the internal anticorrosive coating of the pipeline Ø159×8 mm

In order to identify the reasons for IACPC failure, a comprehensive analysis of the study was conducted in two stages. The first stage was a detailed study of the operating conditions of the coated pipe (composition of the operated medium, temperature, pressure, presence of mechanical impurities), operating time and type of polymer material used.

The second stage included laboratory studies of the coating: visual inspection, determination of the thickness of the inner coating according to GOST 31 993–2013, control of dielectric continuity according to ASTM G62, determination of adhesive strength by the pull-off adhesion strength method according to GOST 32 299–2013, investigation of thermokinetic properties by means of differential scanning callometry (DSC). Microstructural studies were carried out using a scanning electron microscope "TESCAN VEGA3 SBH" equipped with a detachable device for energy dispersion analysis.

Results. Microstructural studies of the anticorrosive coating of the tubing (sample No. 1) revealed complete detachment of the coating from the metal with the development of corrosion processes. This indicated that the formation of a corrosion layer with a thickness of approximately 122 microns was due to the prolonged penetration of aggressive components of the transported medium into the metal substrate (Fig. 6). Studies have not revealed any significant deviations or imperfections in the coating, such as local areas with reduced thickness or the presence of shot particles underneath the coating layer. These findings were consistent with the common occurrence of such phenomena during the shot blasting process of the metal surface prior to applying an anti-corrosion system. Based on these results, it could be concluded that the destruction of the coating through this mechanism was not the cause of the observed corrosion processes in this particular case [16]. These signs indicate damage to the anticorrosive coating caused by the operational impact due to the downhole work carried out to remove impurities and plugs in the tubing trunk using chemical reagents — hydrochloric acid treatments. It was also impossible to exclude an overpressure in the system, as a result of which gas penetrated into the coating volume as a result of diffusion permeability and its sharp expansion, which contributed to the destruction of the coating by decompression mechanism with the formation of blisters [1].

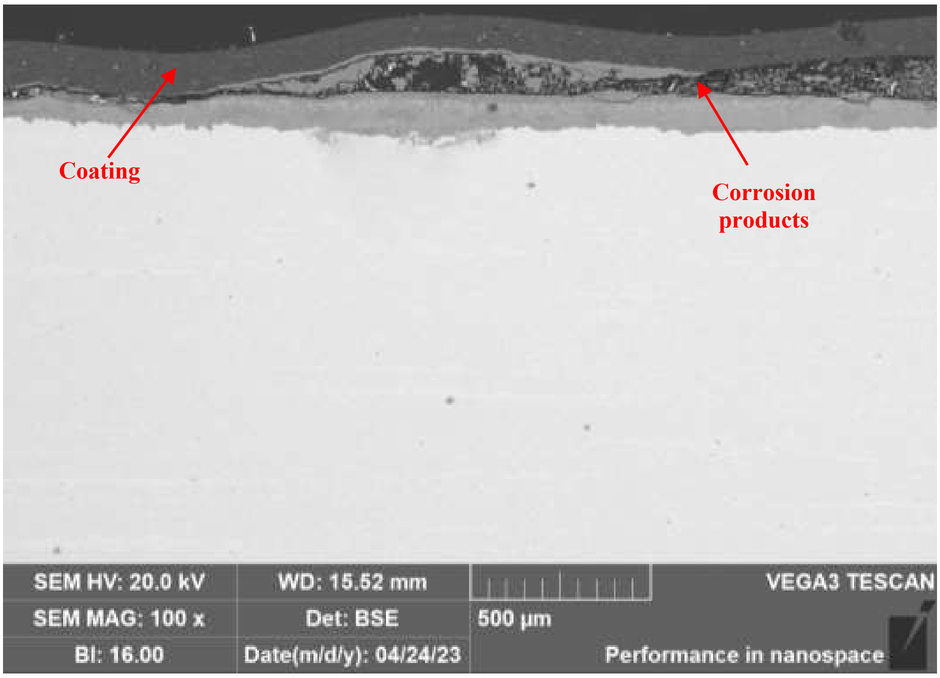
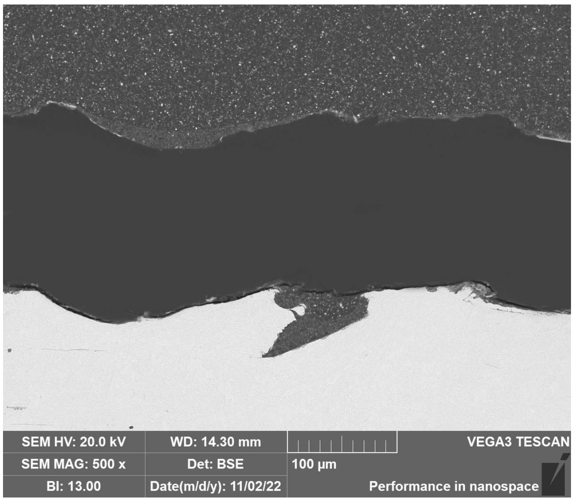


Fig. 6. Microstructural studies of the anticorrosive coating in the area of its damage

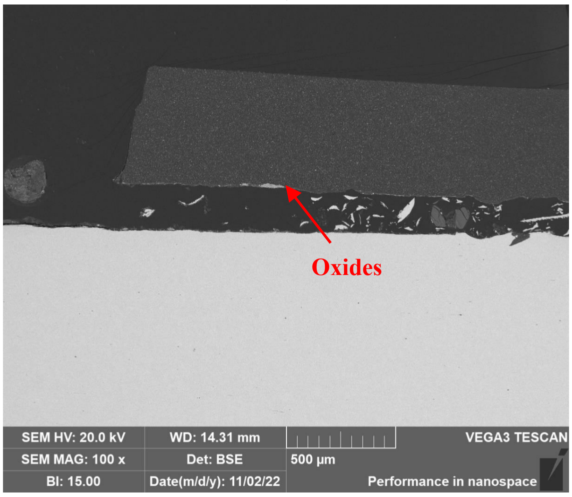
According to the results of the study of the tubing fragment (sample No. 2), no deviations were found in areas where the coating remained intact. However, there was a two-fold decrease in the adhesive strength of the coating in the nipple area compared to the central part of the tube. The thermokinetic characteristics were determined by differential scanning spectroscopy (DSC) with determination of the glass transition temperature (Tg) of the coating along the entire length of the tubing. The results of the analysis did not reveal a significant variation in Tg values of the studied areas, which may indicate uniform heating during the polymerization of the coating.

Microstructural analysis of the anticorrosive system has established that the peeling of the coating occurred along the primer layer and was characterized by a cohesive nature of destruction. In addition, oxide particles were present on the surface of the metal of the pipe and the detached part of the coating (Fig. 7, Table 1). In this case, inclusions of iron oxides on the inner surface of the pipe may have formed due to inadequate cleaning and surface preparation prior to coating.

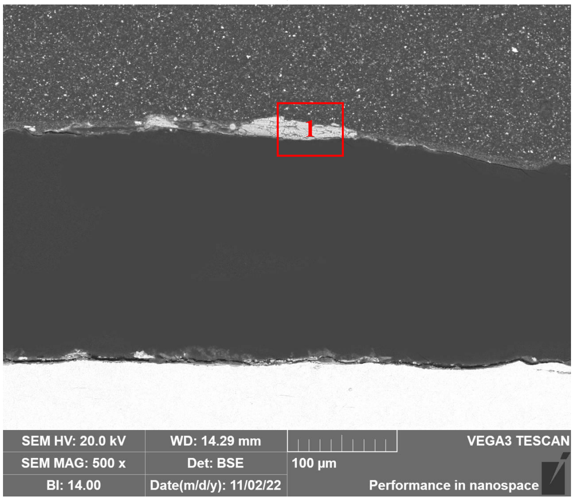
The considered example was a frequent case of destruction of the polymer coating associated with a violation of the technological processes of preparing the inner surface of the pipe before painting.



a)



b)



c)

Fig. 7. Microstructural studies of the coating in the area of its destruction:
a — peeling of the coating from the metal;
b — presence of a layer of oxides; *c* — chemical composition of oxides

Table 1

Chemical composition of the oxide layer, weight %

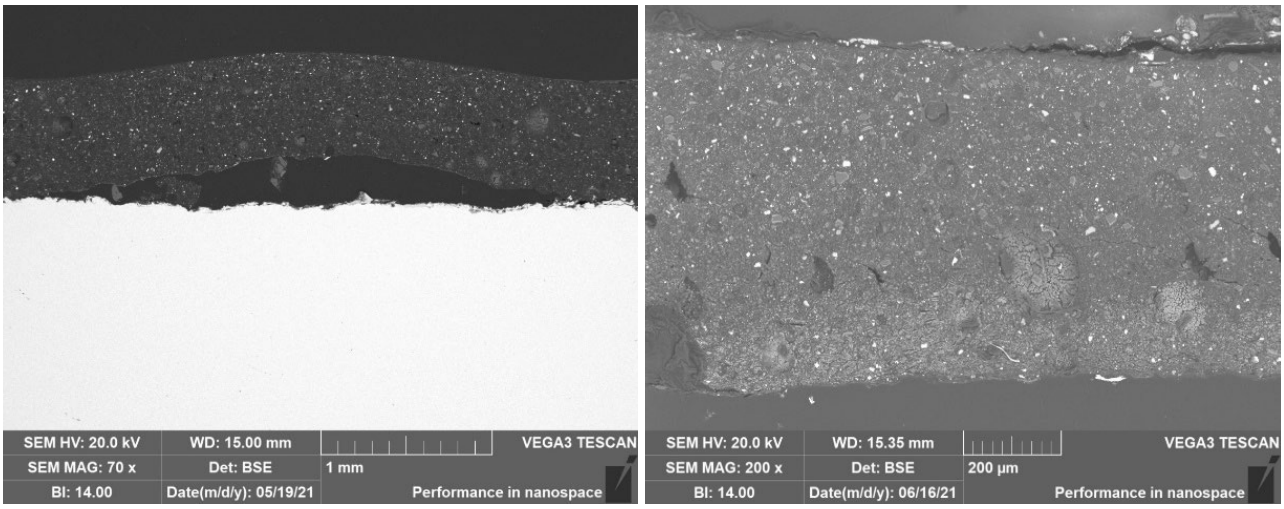
Element/Area	C	O	Si	Mn	Fe
1	19.10	27.31	0.83	0.24	50.78

Upon visual inspection of the inner surface of the tubing (sample No. 3), it was found that the anticorrosive coating had a different shade. No visible coating defects, such as blisters, separations, or cracks, were found. However, when determining the dielectric continuity in the area with the dark brown coating (Fig. 3b), numerous breakdowns were detected, indicating a possible violation of the polymer's integrity due to the presence of microcracks. Taking into account the results of the conducted research, it could be concluded that the heterogeneity in the shade of the anticorrosive coating was likely due to under-polymerization during the drying process. Polymerization is achieved through exposure to high temperatures in specialized ovens, where chemical reactions between polymer chains take place. To ensure uniform heating of the coating during the curing process, it is essential to maintain a constant temperature. Any violation of the temperature-time polymerization regime directly affects the rate of chemical reactions, and as a result, can lead to the destruction of the polymer.

Quite often, there are cases of damage to the anticorrosive coating caused by human error. The formation of coating damage occurs accidentally and it is impossible to predict their occurrence in advance. These defects can occur at different stages, from the production of pipes to their transportation to the consumer. Specifically, the following factors can contribute to the occurrence of these defects: improper selection of coating material for operating conditions, mechanical damage due to lifting and lowering operations or scraping, violations of regulations during transportation and storage of coated pipe products, and the influence of human error.

As an example, we can consider damage to the powder-based inner coating caused by repair work on Ø325x8 mm pipeline (sample No. 4). The damage to the coating was severe, leading to the exposure of the metal substrate and the formation of a through defect in the pipe. External signs, such as the presence of blisters and a change in the color of the coating to black, indicated an additional temperature effect on the pipe at temperatures above 250°C (Fig. 4 *a*). In this case, welding work carried out during repair of the pipeline resulted in the formation of burns and burnouts in the coating (Fig. 4 *b*), due to violation of integrity and continuity of the coating. As a result, the transported medium could easily penetrate through the polymer layer to the metal of the pipe, activating corrosion processes. The intensity of corrosion in a pipeline could be increased by the presence of corrosive substances in the transported fluid, such as dissolved gases like CO_2 and H_2S. It could also be influenced by factors such as the velocity of the fluid flow, temperature, and pressure within the pipeline.

There are often cases where the destruction of an anticorrosive coating can have a complex mechanism and be accompanied by a combination of several factors. Microstructural studies of the Ø325×8 pipeline showed that the destruction of the coating occurred through the mechanism of decompressive peeling, which happened under the influence of a sudden pressure drop [1]. The penetration of gases through the coating reduced the barrier properties of the anticorrosive coating, leading to the development of corrosion on the pipe metal and the formation of corrosion products (Fig. 8). In addition, given the scale and nature of the destruction of the anticorrosive coating layer, it could be established that the main cause of damage to the pipeline was a local thermal effect applied from the inner surface of the pipe. In this case, high-temperature heating led to overheating of the internal anticorrosive coating and its destruction.



a) *b)*

Fig. 8 Microstructural studies of anticorrosive coating in the field of destruction: *a* — peeling of the coating; *b* — destruction of the polymer coating

Discussion and Conclusion. Having studied practical examples of damage to internal anticorrosive coatings, it is possible to divide the causes of their destruction into three groups: operational, technological and defects formed during transportation, storage and construction and installation works.

Operational defects can be associated with various external influences, such as the use of hydrochloric acid treatments and the presence of mechanical impurities. The most common is exceeding the maximum permissible temperature for this type of coating (usually 20–30°C below the glass transition temperature) or high partial pressures of hydrogen sulfide (H_2S) and carbon dioxide (CO_2).

A comprehensive assessment of the coating's ability to withstand operational impacts in the conditions of oil production and transportation can be conducted in accordance with GOST 58 346–2019[1] and regulatory documents developed on its basis[2, 3, 4]. Despite discrepancies in the methods of autoclave testing, all the presented documents can adequately assess the IACPC quality. However, predicting the resource of trouble-free operation based on them is impossible. The development of a model for accident-free resource forecasting is the most urgent task. It, in turn, is based on the accumulation, description and systematization of the causes of the IACPC destruction.

Technological defects include all defects and imperfections formed during the preparation of the pipe surface before painting and applying (polymerization) of internal coatings. Obtaining the necessary properties for a specific coating system is possible if the preparation requirements specified in Table 2 are met. For powder thermohardening coatings, criterion $\Delta Tg \leq 3°C$ must be met. It is possible to control the degree of hardening of liquid coatings only by indirect methods, for example, by comparing the Buchholz hardness of the controlled coating with the reference one.

Table 2

Requirements for the inner surface

Parameter	Indicator	Standard	Test method
Degree of degreasing	No more than	1	GOST 9.402
Presence of oxides	Degree of purification, not less than	Sa 2.5	GOST R ISO 8 501–1
Dustiness	Amount of dust, no more than	2 points	ISO 8 502–3
	Size of the dust particles, no more than	2 class	
Roughness	Average height of microroughness Rz, microns, within	40–100	ISO 8 503–2
Presence of water-soluble salts	Salt content mg/m^2, no more than	20	ISO 8 502–6 ISO 8 502–9

Defects that may occur during transportation, storage, construction, and installation can be minimized only with an increased focus on production quality and/or the implementation of inspection and construction control.

The compliance with the presented recommendations makes it possible to obtain IACPC with a guaranteed lifespan of at least 15 years under the conditions of Western Siberia, as confirmed by the successful operation of similar pipelines at Surgutneftegaz PJSC and LUKOIL – Western Siberia LLC.

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PE Yudin: formulation of the basic concept, goals and objectives of research, formulation of the conclusions.

AP Amosov: academic advising, discussion of the research results, revision of the text, correction of the conclusions.

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