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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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Technical Solutions to Reduce the Amount of Dust Particle Breakthrough when Cleaning Emissions from the Production of Reinforced Concrete Products Using Dust Collectors with Counter Swirling Flows

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Abstract

Introduction. The production of reinforced concrete products, being the basis of modern industrial construction, is a very significant source of dust emissions. Traditional cleaning methods are often unable to ensure the compliance with air quality requirements, and replacing them with more modern ones requires significant capital and operational costs. One of the most promising ways to solve the problem is the use of a new class of inertial dust collectors with counter swirling flows, combining constructive simplicity and low operating costs with sufficiently high work efficiency. The aim of the work was to analyze the factors influencing the magnitude of the breakthrough coefficient of fine dust particles, as well as the development of constructive solutions aimed at reducing it.

Materials and Methods. An analytical review of technical solutions aimed at reducing the breakthrough magnitude was carried out, on the basis of which the designs of the lower input of dust collectors with counter swirling flows were developed. Methods of computational experiment and field measurements were used to confirm the effectiveness of the developed structures.

Results. By means of numerical experiments, the information about the aerodynamic flow pattern in the separation chamber of the CSF dust collector was obtained, and the breakthrough magnitude of dust particles was estimated. The solutions were developed for the design of the lower coaxial input of the swirling flow of dust collectors on the counter swirling flows, taking into account the features of dust pollution generated during the operation of technological equipment of reinforced concrete production.

Discussion and Conclusion. The presence of a displacement of the axis of the secondary swirling flow from the axis of symmetry of the separation chamber was established. The consequence of this was the non-coaxiality of the primary and secondary flows, which led to a decrease in the intensity of the twist, the formation of parasitic vortices, and, as a consequence, an increase in the value of the breakthrough coefficient. This effect was especially pronounced with a large proportion of fine dust particles, characteristic of dust pollution formed during the production of reinforced concrete products. The proposed design of the coaxial input of the secondary swirling flow reduced the magnitude of this eccentricity, which made it possible to achieve a significant reduction in the breakthrough magnitude of fine particles characteristic of dust emissions of reinforced concrete industries. The results obtained can be effectively used both in the production of reinforced concrete products and in other branches of construction production, which is characterized by intensive formation of fine dust emissions.

Keywords: dust collector with counter swirling flows, dust particle breakthrough coefficient, enterprises for the production of reinforced concrete products and structures

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Научная статья

Технические решения по снижению величины проскока пылевых частиц при очистке выбросов производства железобетонных изделий пылеуловителями со встречными закрученными потоками

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Аннотация

Введение. Производство железобетонных изделий, будучи основой современного индустриального строительства, является весьма существенным источником пылевых выбросов. Традиционные методы очистки зачастую неспособны обеспечить соблюдение требований к качеству воздушной среды, а замена их более современными требует значительных капитальных и эксплуатационных затрат. Одним из наиболее перспективных путей решения проблемы является применение нового класса инерционных пылеуловителей со встречными закрученными потоками, сочетающими конструктивную простоту и низкие эксплуатационные затраты с достаточно высокой эффективностью работы. Целью работы был анализ факторов, оказывающих влияние на величину коэффициента проскока мелкодисперсных пылевых частиц, а также разработка конструктивных решений, направленных на его снижение.

Материалы и методы. Проведен аналитический обзор технических решений, направленных на снижение величины проскока, на основании которых разработаны конструкции нижнего ввода пылеуловителей со встречными закрученными потоками. Для подтверждения эффективности разработанных конструкций применялись методы вычислительного эксперимента и натурные замеры.

Результаты исследования. Посредством проведения численных экспериментов получены сведения об аэродинамической картине течения в сепарационной камере пылеуловителя ВЗП, а также произведена оценка величины проскока пылевых частиц. Разработаны решения по конструктивному оформлению нижнего коаксиального ввода закрученного потока пылеуловителей на встречных закрученных потоках, учитывающие особенности пылевых загрязнений, образующихся при работе технологического оборудования железобетонного производства.

Обсуждение и заключение. Было установлено наличие смещения оси вторичного закрученного потока от оси симметрии сепарационной камеры. Следствием этого является некоаксиальность первичного и вторичного потоков, приводящая к снижению интенсивности закрутки, образованию паразитных вихрей, и, как следствие, увеличению значения коэффициента проскока. Особенно сильно данный эффект проявляется при большой доле мелкодисперсных пылевых частиц, характерной для пылевых загрязнений, образующихся при производстве железобетонных изделий. Предложенная конструкция коаксиального ввода вторичного закрученного потока снижает величину данного эксцентриситета, что позволяет достигать существенного снижения величины проскока мелкодисперсных частиц, характерных для пылевых выбросов железобетонных производств. Полученные результаты могут быть эффективно использованы как в производстве железобетонных изделий, так и в других отраслях строительного производства, для которого характерно интенсивное образование мелкодисперсных пылевых выбросов.

Ключевые слова: пылеуловитель со встречными закрученными потоками, коэффициент проскока частиц пыли, предприятия по производству железобетонных изделий и конструкций

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и указанные замечания, которые позволили повысить ее качество.

Для цитирования. Месхи Б.Ч., Евтушенко А.И., Боровков Д.П. Технические решения по снижению величины проскока пылевых частиц при очистке выбросов производства железобетонных изделий пылеуловителями со встречными закрученными потоками. *Безопасность техногенных и природных систем.* 2023;7(4):7–19. https://doi.org/10.23947/2541-9129-2023-7-4-7-19

Introduction. The designs of dust-collecting devices for dust and gas cleaning are gradually becoming more complicated [1–5], which is accompanied by an increase in the costs of their production. This circumstance makes it difficult to widely use new types of dust collectors: wet washing devices, electric filters, fabric dust collectors of various types. Modern requirements in the field of air cleanliness require the expansion of the use of dust collecting devices and increasing the efficiency of their operation [6]. A promising way to resolve this contradiction is to improve inertial methods of dust collection, characterized by constructive simplicity and low cost of operation. One of the directions of development of inertial methods of dust collection is dust collectors on counter swirling flows (hereinafter referred to as CSF). Their main advantage is lower values of the dust breakthrough coefficient compared to cyclones, the stability of work and the simplicity of structures [6]. However, the spread of this type of dust collectors is constrained by insufficient information on the effectiveness of application in specific areas of industrial production. In addition, there is a wide variety of design schemes of such devices, each of which requires fine-tuning in the conditions of a specific technological process. Therefore, the development of technical solutions for the adaptation of dust collectors on counter swirling flows is an urgent task.

There are two main types of dust collectors on counter swirling flows. The first type includes devices in which compressed air is used to create a secondary swirling flow. The inlet through which compressed air is supplied is located on top and is called secondary. The second type includes devices created on the basis of cyclones [6–8]. The main difference between CSF devices and cyclones is that a lower inlet is added to the usual upper inlet. A patent was obtained by E. Schaufler and H. Zennek for the described designs in 1953 (Fig. 1) [9].

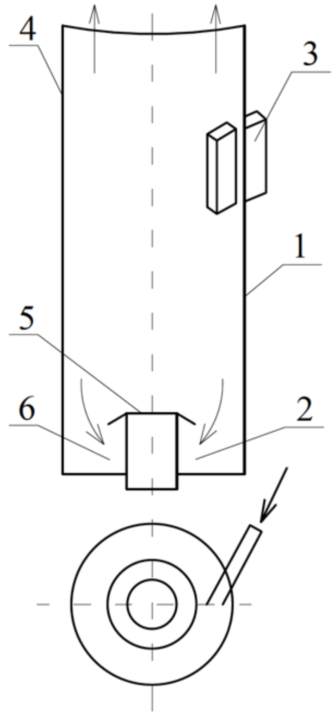
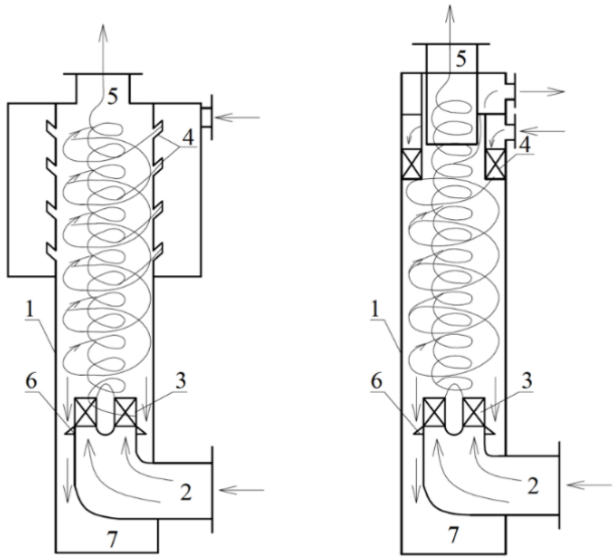


Fig. 1. Vortex chamber for separation of solid and liquid aerosol particles by means of an auxiliary swirling gas flow:
1 — separator; 2 — primary flow inlet; 3 — nozzle for secondary flow;
4 — exhaust pipe; 5 — jack washer; 6 — dust collection hopper [10]

In 1972, the designs of nozzle (Fig. 2 *a*) and vane (Fig. 2 *b*) types were proposed [6].



a) *b*)

Fig. 2. Vortex dust collectors: *a* — nozzle type:
1 — chamber; 2 — inlet pipe; 3 — vane swirler of the "socket" type; 4 — nozzles; 5 — outlet pipe;
6 — retaining washer; 7 — dust hopper; *b* — vane type: 1 — chamber; 2 — inlet pipe; 3 — vane swirler of the "socket" type;
4 — annular vane swirler; 5 — outlet pipe; 6 — retaining washer; 7 — dust hopper [10]

The exclusion of inertial dust collectors from the layout schemes of cleaning systems, as well as the use of cyclones of outdated design as the first stage, negatively affects the resource, energy efficiency and operating costs. Dust collectors on counter swirling flows, due to the increased efficiency of separation of medium and small fraction particles, can significantly relieve more expensive and energy-intensive dust collecting equipment, increasing the operational characteristics of emission purification systems and reducing the cost of their operation.

Currently, the study of CSF devices and their introduction into various productions are conducted by several research teams of Russia. In the works of V.N. Azarov, S.A. Koshkarev, N.M. Sergina, D.P. Borovkov, etc. a number of design changes in the CSF devices have been proposed, and various schemes of dust cleaning systems have been developed, in which cyclones, CSF and bag filters are used [6]. For example, in order to increase the reliability of operation of CSF devices, including at the factories of the concrete industry, it is proposed in a number of designs to take the bottom inlet vortex generator outside the devices [6, 11]. In addition, a number of devices with several upper inlets have been developed, for example, dust collectors (Fig. 3) [6].

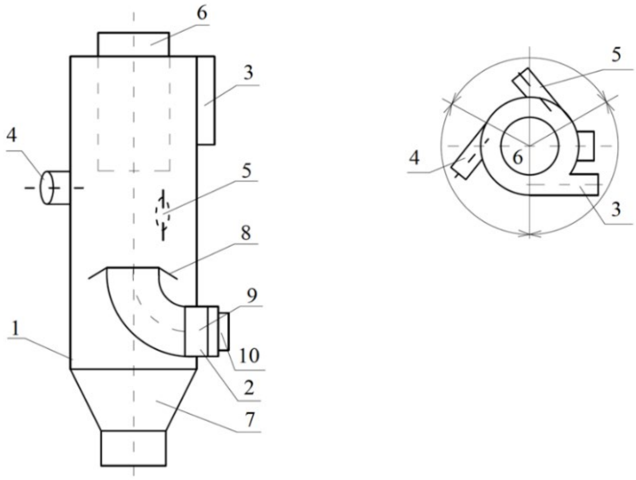


Fig. 3. Diagram of the DC-CSF dust collector:
1 — housing; 2 — inlet of the secondary dust flow; 3, 4, 5 —inlets of the primary dust flow;
6 — outlet of the purified air; 7 — dust collector;
8 — jack washer; 9 — swirler; 10 — hatch for cleaning [10]

Works by E.I. Boguslavskiy, V.N. Azarov and others are devoted to stochastic models for CSF calculation [6, 11]. In works [12–15], the calculations of fractional efficiency of CSF devices using modern software systems were carried out.

As follows from the analysis of literature sources on this topic, at present, the design schemes of CSF dust collectors differ mainly in the type of secondary flow inlet (with an external and internal vortex generators), and the main efforts of researchers are aimed at studying aerodynamic parameters and creating calculation techniques. However, it is the improvement of the design of the secondary inlet that allows reducing the value of the breakthrough coefficient. The main feature characteristic of dust particles formed during the production of reinforced concrete products is their fine dispersion [16, 17]. Particles of small fractions are more prone to slip, especially in conditions of insufficient intensity of the secondary flow twist. One of the factors influencing the intensity of the twist is the geometric configuration of the secondary inlet, which introduces serious distortions into the kinematic structure of the flow in the lower region of the separation chamber of the CSF dust collectors [17]. In addition to reducing the overall intensity of the flow twist, when it interacts with the secondary inlet pipe, undesirable idle vortices occur that can cause entrainment of already captured dust particles [18].

The aim of this study was to analyze the factors that had a decisive influence on the value of the breakthrough coefficient of fine dust particles of reinforced concrete production and to develop appropriate design solutions for the design of the lower inlet of the swirling flow of CSF dust collectors.

Materials and Methods. The study of the parameters of movement of dust-air mixture in the lower part of the separation chamber of the dust collector with counter swirling flows was carried out by means of a computational experiment. The kinematic model of the motion of gas dust collector in the separation chamber on the counter swirling flows, implemented using the numerical solution of Navier-Stokes equations and continuity, was closed using the *k*-*ε* turbulence model in the COSMOSFlowWorks application for the SolidWorks software.

To solve this problem, models of CSF dust collector of several standard sizes with standard strapping were built. The dimensions of the main elements of the vortex dust collector were accepted as typical for CSF and CIF series of vortex dust collectors. Dust collectors with separation chamber diameters of 160, 350 and 700 mm were used as prototypes in the construction of models. Figure 4 provides the scheme of a computational model (made with the use of SolidWorks numerical modeling environment). At the first stage, initial and boundary conditions were set to bind the mathematical model to a specific task and to the computational domain.

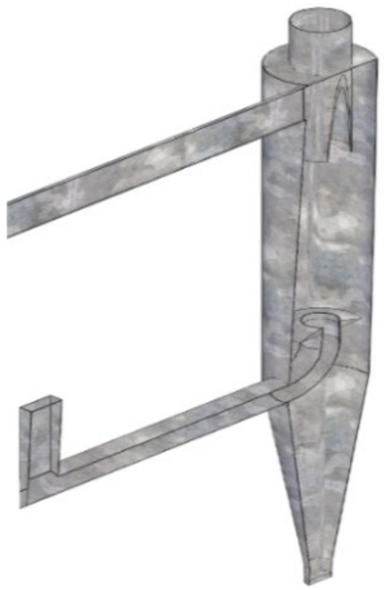


Fig. 4. Scheme of computational model of vortex dust collector

The experimental research plan included three series of experiments conducted for different values of the flow rate supplied to the inlet section of the lower vortex generator (zone B) (Fig. 5).

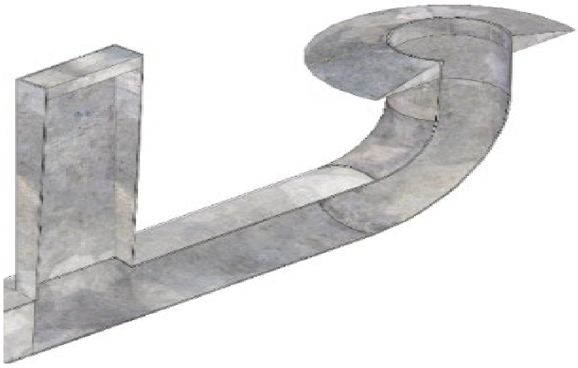


Fig. 5. Cross section of the lower inlet pipe of the secondary dust and gas flow of the CSF dust collector

The scheme for determining the design parameters of the lower inlet is shown in Figure 6 (made with the use of SolidWorks numerical modeling environment).

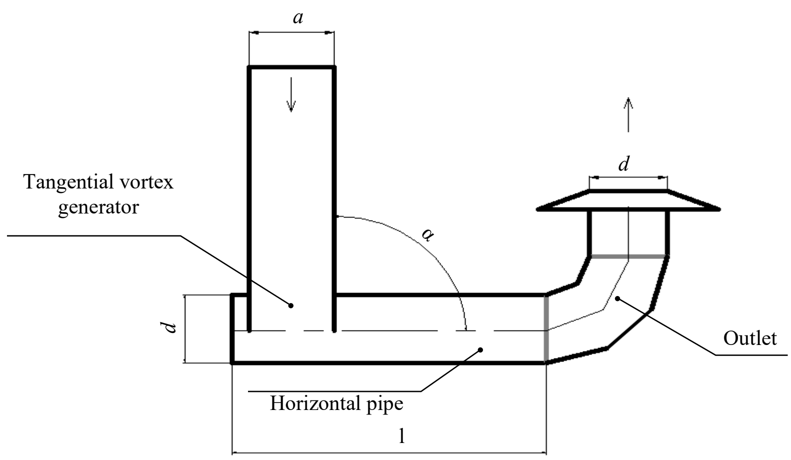
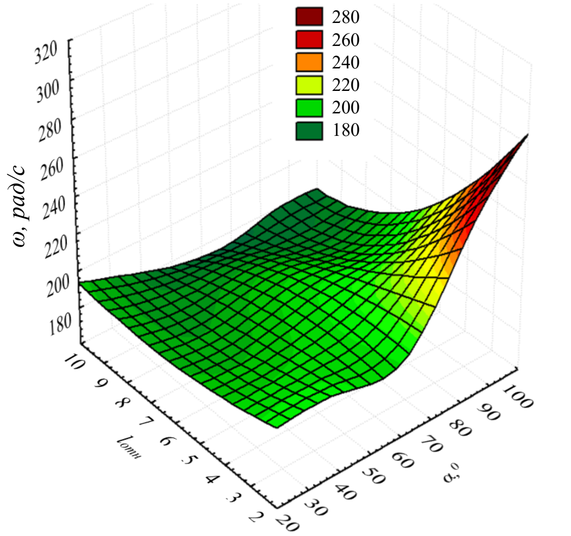


Fig. 6. Characteristic design dimensions of the secondary flow vortex generator:
l — length of the swirling flow pipe related to the diameter (*d*);
a — relative width of the tangential branch pipe related to the diameter (*d*);
α — angle of entry of the tangential pipe

After calculating the values of gas flow velocities characterizing the flow field in the calculated sections, the trajectories of dust particles of fractions characterized by the values of equivalent diameters of dust particles $d_ч$ = *10–100 microns* were calculated. Based on the results obtained, the fraction of the number of particles entering the volume of the separation chamber of the vortex dust collector through the upper and lower inlets was calculated. Also, for the aerodynamic modes specified by the range of values of the average Reynolds numbers Re = 8 700–28 000 over the section of the separation chamber, the values of the aerodynamic drag of the dust collector and angular velocities in the wall zone of the separation chamber, which had a determining value on the magnitude of the dust particle breakthrough, were calculated.

Full-scale measurements of the breakthrough coefficient were carried out on the existing dust collectors in accordance with standard measurement methods in NIIOGAZ dispersion flows using Pitot pneumatic tubes, micromanometers MMN – 250, electric respirators, and AFA filters.

Results. Figures 7–9 (made with the use of SolidWorks numerical simulation environment) present the results of calculations of angular velocity values obtained during the variation of design characteristics of the lower inlet at Re = 8 700–28 000 in the form of response surfaces.



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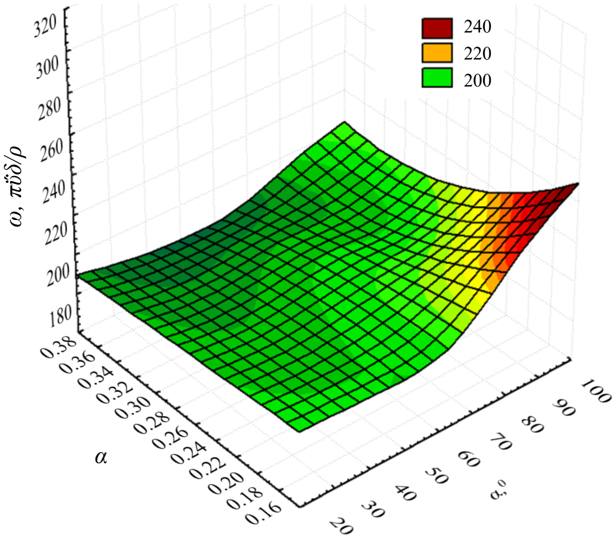
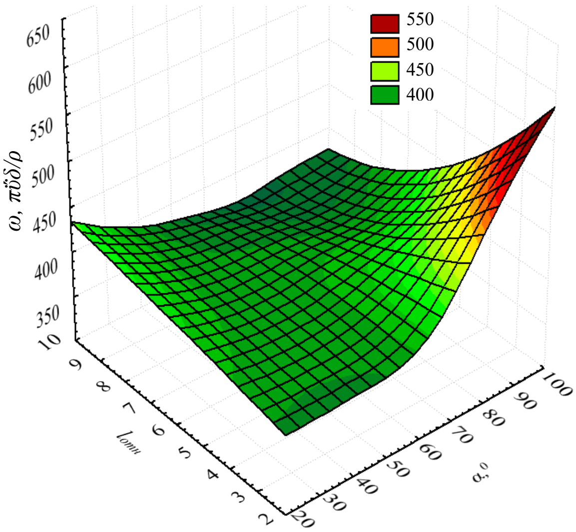


b)

Fig. 7. Results of calculations of angular velocity values ω, rad/s, at Re = 8,700:
a — dependence of angular flow velocity on the values of relative length of the branch pipe of the swirling flow of the angle of entry of the tangential branch pipe ω ($l_{отн}$;α); *b* — dependence of angular flow velocity on the values of the relative width of the tangential branch pipe of the flow and the angle of entry of the tangential pipe ω ($l_{отн}$;α).



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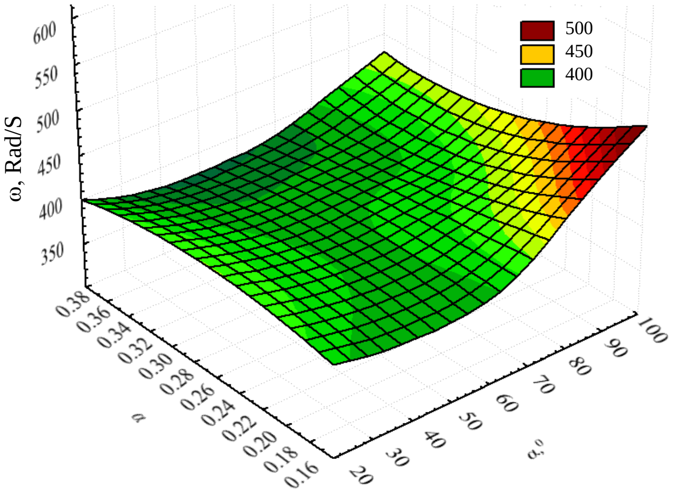
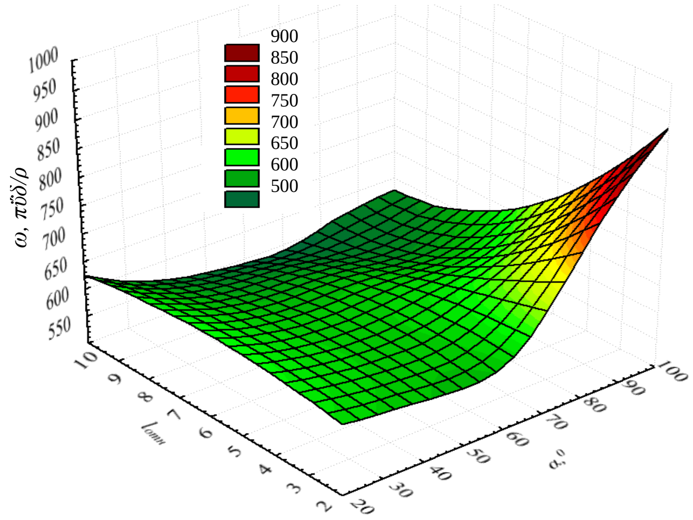


b)

Fig. 8. Results of calculations of tangential velocity values ω, rad/s, at Re = 17,900:
a — dependence of angular flow velocity on the values of the relative length of the swirling flow branch pipe and the angle of entry of the tangential branch pipe ω ($l_{отн}$;α); *b* — dependence of angular flow velocity on the values of the relative width of the tangential branch pipe and the angle of entry of the tangential branch pipe ω ($l_{отн}$;α)



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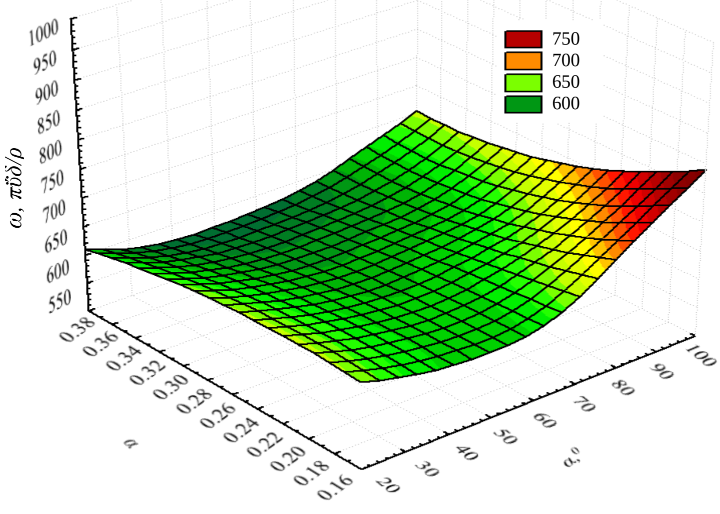

b)

Fig. 9. Results of calculations of angular velocity values ω, rad/s, at Re = 28,000:
a — dependence of angular flow velocity on the values of the relative length of the swirling flow branch pipe and the angle of entry of the tangential branch pipe ω ($l_{отн}$;α); *b* — dependence of angular flow velocity on the values of the relative width of the tangential branch pipe and the angle of entry of the tangential branch pipe ω ($l_{отн}$;α)

Figure 10 (made with the use of SolidWorks numerical simulation environment) shows the distribution of tangential velocities values of the gas flow along the section of the separation chamber at the cut-off level of the secondary flow outlet pipe.

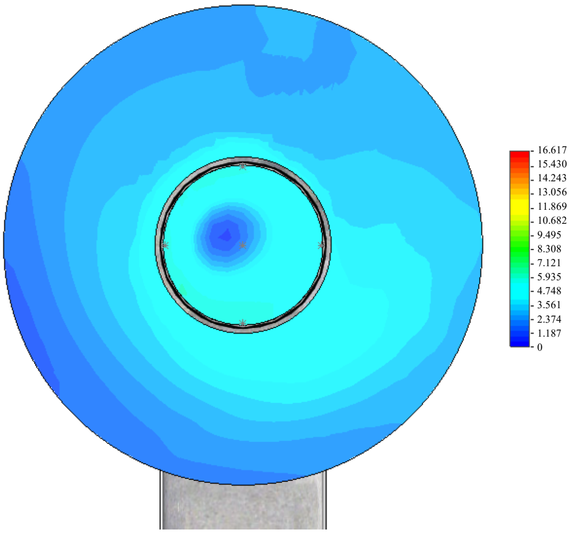

Fig. 10. Distribution of tangential velocities values of gas flow along the section of the separation chamber at the cut-off level of the secondary flow outlet pipe (m/s)

To clean the dust emissions of reinforced concrete production, a design of a CSF dust collector with an axial secondary flow supply for the use in reinforced concrete plants was proposed (Fig. 11) [19].

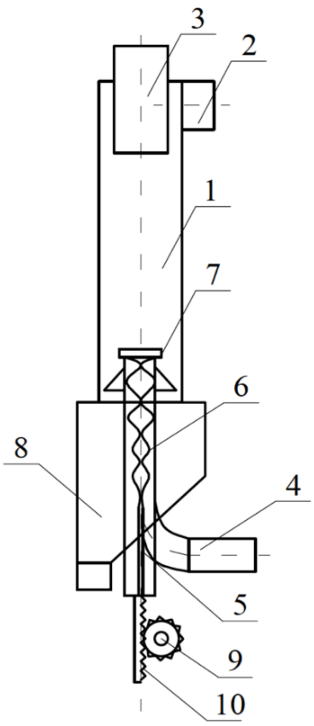

Fig. 11. Diagram of the device of a vortex dust collector with a screw-type swirler: 1 — cylindrical separation chamber; 2 — tangential inlet of the cleaned flow; 3 — coaxial exhaust pipe; 4 — axial pipe of primary inlet; 5 — screw type vortex generator; 6 — screw swirler; 7 — conical jack washer; 8 — dust collection hopper; 9 — gear wheel; 10 — gear rack [19]

At the second stage, full-scale measurements of the values of the breakthrough coefficient for fine dust of enterprises producing reinforced concrete products were carried out on standard CSF dust collectors and on the devise of the proposed design. The dependencies obtained in the course of experimental studies are shown in Figure 12. For comparison, the figure also shows the results obtained during the tests of the CSF of the classical design (curve 4).

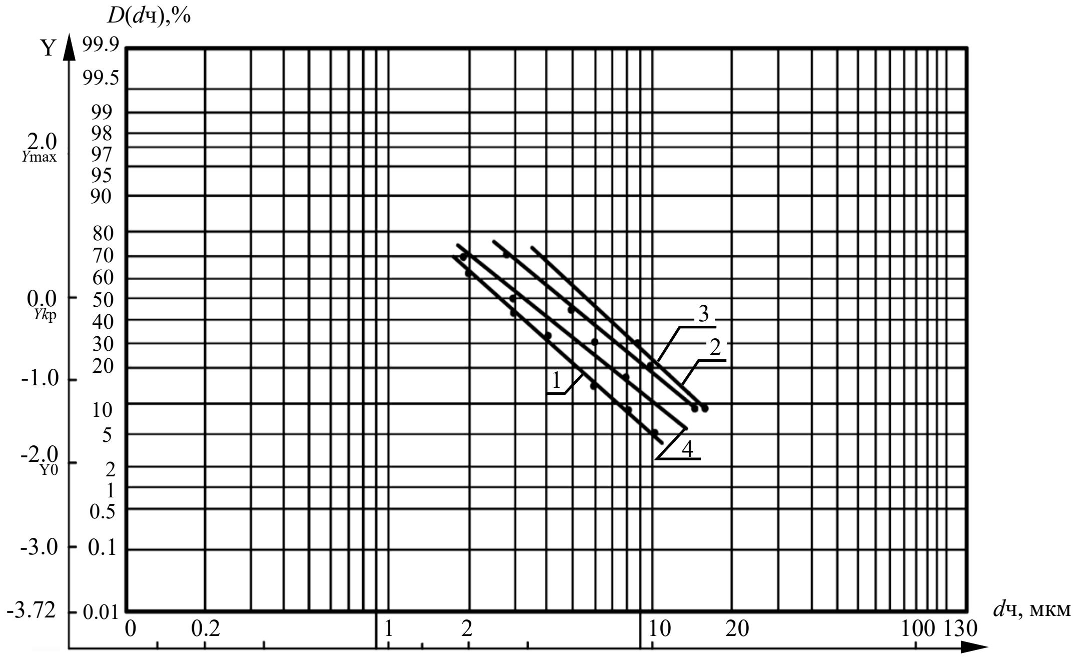

Fig. 12. Results of experimental studies of the breakthrough functions of the CSF dust collectors:
1 — CSF-200; 2 — CSF-400; 3 — CSF-600 with coaxial inlet; 4 — CSF-200 designs by V.D. Kononenko

Discussion and Conclusion. The results obtained during computational experiments strongly support the assumption that there is a negative influence of the secondary inlet pipe on the kinematic structure of the flow in the lower part of the separation chamber of dust collectors on counter swirling flows. From the data presented in Figure 10, it follows that the axis of rotation of the flow is offset from the axis of the separation chamber. This leads to a decrease in the useful effect of the vortex effect, which consists in increasing the intensity of the twist due to the interaction of unidirectionally twisted flows.

The mismatch of the axis of rotation of the swirling flow with the axis of the separation chamber, which is also the axis of rotation of the primary swirling flow formed by the upper tangential inlet, leads to a noticeable increase in the magnitude of dust particles breakthrough. This fact is explained by the formation of idle vortices at the confluence boundaries of non-coaxial swirling flows. The consequence of this is carrying-away of dust particles already caught or trapped in the wall zone. Being torn out of the wall stream, or blown up by an idle vortex, dust particles fall into the secondary stream, and, due to its opposite orientation, are carried away into the pure gas pipe.

It should be noted that this effect is most pronounced on particles of small fractions, which are characterized by a significant predominance of aerodynamic forces over mass ones. And it is this fact that makes the task of eliminating the negative influence of the secondary branch pipe, which introduces undesirable distortions during the secondary swirling flow, especially relevant in the conditions of using CSF devices in reinforced concrete production, for which dust emissions are characterized by the presence of a large proportion of fine dust particles.

To eliminate the described problem, the use of a coaxial inlet of the secondary flow is proposed (Fig. 12). The main feature of the proposed design of the vortex dust collector is the use of a coaxial inlet of the secondary swirled flow, achieved through the use of screw-type twirlers. The use of such a layout scheme makes it possible to optimize the movement of the swirling flow in the lower part of the separation chamber, as well as reduce the likelihood of suction. The absence of a radial branch pipe of the secondary flow that overlaps a part of the live section of the separation chamber of dust collectors of traditional design allows avoiding undesirable disruption of the kinematic structure of the flow. The absence of idle swirls of the flow in the lower part of the separation chamber makes it possible to significantly reduce secondary carrying-away of dust particles located in the wall zone of the flow, which, in turn, reduces the total amount of dust particle breakthrough. In addition, the use of coaxial inlets makes it possible to obtain some reduction in the aerodynamic drag of CSF dust collectors, increasing their energy efficiency.

The proposed design of the coaxial inlet of the secondary swirling flow allows us to solve the problem. This fact is confirmed by the results of pilot tests, the results of which are shown in Figure 12. Curve 3, which characterizes the function of dust particles breakthrough in the device with a coaxial inlet, is located above the others, which indicates a smaller breakthrough of particles of all fractions.

Thus, the use of dust collectors on counter swirling flows with coaxial secondary inlet at enterprises producing reinforced concrete products makes it possible to achieve a high degree of purification of dust emissions without resorting to expensive replacement of inertial dust collectors with devices of other types.

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Original article

Main Scientific Principles of a Systematic Approach to the Determination of Negative Factors Affecting Urban Environment

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Abstract
Introduction. With the modern active development of urban areas, the problems in the field of environmental safety are becoming increasingly relevant. These problems cannot be solved without an in-depth analysis of the factors that disrupt the ecological balance and cause negative consequences for the components of the environment. At the same time, construction industry is one of the main elements of human economic activity that forms technogenic loads. This is due, among other things, to the fact that, unlike some other areas, the pace of construction work has increased significantly over the past year. So, as of March 2023, 2 460 developer organizations were registered in the Russian Federation, which was 14% more than in the previous period, that is, the speed and scale of construction work most of all affect the population of cities from a socio-economic point of view. At the same time, we should not forget about the environmental side of the issue. Many years of research in this area has shown the lack of a structured approach to assessing the environmental safety of urban areas, including the selection of an optimal list of environmental measures. At the same time, scientific approaches based on the ecological characteristics of the totality of natural conditions, determining the maximum permissible anthropogenic loads, identifying environmentally significant environmental parameters, such as the amount of oxygen in the atmospheric air or the availability of natural water resources, require significant time and labor costs, and also, as a rule, are not tied to specific objects of the urban environment. However, urban planning spaces, depending on their functional purpose, contain typical anthropogenic objects, among which capital construction and landscaping facilities predominate. The nature of the negative impact on the environment from such facilities is obviously also typical. In this regard, the aim of the study was to systematize and unify numerous negative factors affecting the territory of a particular object of capital construction and landscaping, depending on the functional purpose of the territory and the types of objects located on it. The authors propose to perform such transformations automatically within the framework of the developed online platform.
Materials and Methods. To assess the negative impact on the urban environment, it was proposed to use a methodological approach based on the concept of functional zoning of the territory. According to the Urban Planning Code of the Russian Federation, each functional zone is characterized by the presence of certain capital construction and landscaping facilities. To achieve this goal, we used methods of comparative and system analysis and generalization. Thus, the results were obtained and systematized in the work, which showed the similarity of the nature of the negative impact from the same types of capital construction and landscaping facilities.
Results. The assessment of the negative impact of capital construction and landscaping facilities on the environment was part of the research work prepared within the framework of the state program "Priority 2030". A systematic approach in analytical studies of negative factors of urban environment will allow structuring information, significantly speeding up its analysis and making appropriate decisions due to the relationships we have established between the parameters of negative factors, types of objects and functional zones in which they were located. The proposed approach was implemented within the framework of the online platform developed by the authors. At the same time, the

main principle that guided us was quick access to the task of ensuring environmental safety of the territory due to accelerated automated assessment of negative factors from a given capital construction object or urban improvement.
Discussion and Conclusion. The obtained research results, which include the systematization of negative environmental impact factors on the territories of capital construction and landscaping facilities, depending on the functional zones of their location, are the basis for further development of methods for ensuring environmental safety of the urban environment. The fullest possible identification of all environmentally hazardous factors will ensure an effective assessment of the negative impact on the environment of capital construction projects and urban improvement.

Keywords: environmental safety, negative impact assessment, environment, capital facilities, landscaping, urban environment

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Научная статья

Основные научные принципы системного подхода к определению негативных факторов, воздействующих на окружающую среду городских территорий

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Аннотация
Введение. В современных условиях активного развития городских территорий проблемы в области обеспечения экологической безопасности приобретают все большую актуальность. Они не могут быть решены без глубокого анализа факторов, нарушающих экологическое равновесие и вызывающих негативные последствия для компонентов окружающей среды. При этом одним из главных элементов хозяйственно-экономической деятельности человека, формирующей техногенные нагрузки, выступает строительная отрасль. Это связано в том числе с тем, что, в отличие от некоторых других сфер, темпы строительных работ за последний год значительно возросли. Так, на март 2023 года в Российской Федерации зарегистрировано 2460 организаций-застройщиков, что на 14 % больше предыдущего периода, то есть скорость и масштаб строительных работ в настоящее время больше всего затрагивают население городов с социально-экономической стороны. Но при этом нельзя забывать и об экологической стороне вопроса. Многолетний опыт исследований в этой сфере показал отсутствие структурированного подхода к оценке экологической безопасности городских территорий, включающего в себя подбор оптимального перечня природоохранных мероприятий. При этом научные подходы, основанные на экологической характеристике совокупности природных условий, определении предельно допустимых техногенных нагрузок, выявлении экологически значимых параметров окружающей среды, таких как количество кислорода в атмосферном воздухе или наличие естественных водных ресурсов, требуют значительных временных и трудовых затрат, и они, как правило, не привязаны к конкретным объектам городской среды. Однако градостроительные пространства в зависимости от функционального назначения содержат типовые антропогенные объекты, среди которых преобладают объекты капитального строительства и благоустройства территорий. Характер негативного воздействия на окружающую среду таких объектов, очевидно, является тоже типовым. В связи с этим целью данного исследования является систематизация и унификация многочисленных негативных факторов, воздействующих на те или иные территории объекта капитального строительства и благоустройства, в зависимости от функционального

назначения и территории, и расположенных на ней объектов. Такие преобразования авторы предлагают производить автоматизировано в рамках разработанной онлайн-платформы.
Материалы и методы. Для оценки негативного воздействия на окружающую городскую среду негативных факторов предлагается использовать методический подход, основанный на концепции функционального зонирования территории. Согласно ГрК РФ, для каждой функциональной зоны характерно наличие определенных объектов капитального строительства и благоустройства. Для достижения поставленной в исследовании цели использованы методы сопоставительного и системного анализа и обобщения. Авторами получены и систематизированы результаты, которые показали схожесть негативных воздействий от одних и тех же типов объектов капитального строительства и благоустройства территорий.
Результаты исследования. Оценка негативного воздействия на окружающую среду объектов капитального строительства и благоустройства территорий является частью научно-исследовательской работы, подготовленной в рамках государственной программы «Приоритет-2030». Системный подход к исследованию негативных факторов городской среды позволит структурировать имеющуюся информацию, значительно ускорить ее анализ и принятие на ее основе соответствующих решений за счет установленных авторами взаимосвязей между параметрами негативных факторов, типами объектов и функциональными зонами, в которых они расположены. Предлагаемый подход реализуется в рамках разрабатываемой авторами онлайн-платформы. При этом для обеспечения экологической безопасности территории они руководствуются основным принципом, заключающимся в ускоренном проведении автоматизированной оценки негативных факторов, исходящих от объекта капитального строительства или благоустройства городской среды.
Обсуждение и заключение. Полученные результаты исследований, включающие в себя систематизацию негативных факторов воздействия на окружающую среду территорий объектов капитального строительства и благоустройства в зависимости от функциональных зон их расположения, являются основой для дальнейшей разработки методики обеспечения экологической безопасности городской среды. Максимально полное выявление всех экологически опасных факторов обеспечит возможность всесторонней оценки негативного воздействия на окружающую среду объектов капитального строительства и благоустройства городских территорий.

Ключевые слова: экологическая безопасность, оценка негативного воздействия, окружающая среда, объекты капитального строительства, благоустройство территорий, городская среда

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Introduction. The development of society is inextricably linked with the formation of an appropriate habitat. Scientific and technological progress, discoveries in various spheres of life, the widespread use of mechanisms made it possible to expand the human habitat even in areas that are difficult to develop. At the same time, the possible negative impact on the environment in the process of economic activity began to be talked about a little more than a hundred years ago, and the term "sustainable development" and its principles were first formulated in 1972.

Currently, the issue of ensuring environmental safety of both human habitat as a whole and the individual spheres of life or activity is extremely relevant and discussed. According to the authors, this is due to the fact that there is still no convenient systematic methodology for selecting environmental measures for capital construction and urban facilities. The first step to describe it is to systematize negative factors affecting the components of the environment. At the same time, the analysis of environmental problems shows that they are most clearly manifested primarily in the urban environment, where there is a replacement of natural biogeocenosis with urban- and agrocoenosis, as well as deep inseparable relationships between natural components and elements of highly urbanized territories appear. By highly urbanized territories, the authors of this work understand the territories of megacities, urban agglomerations, and large cities. Such forms of settlements occupy a significant part of the land; most of the world's population is concentrated on them.

The spectrum of impact of highly urbanized territories on the environment turns out to be extremely wide, with the maximum concentration of negative factors. However, as practice shows, project documentation for capital construction and landscaping projects does not prescribe the full range of negative influencing factors, and, as a result, the envisaged project measures to protect the environment do not give the proper effect, since they rely on standard solutions copied from project to project.

Materials and Methods. The works of such domestic and foreign scientists as Vetrov N.M., Verekh T.V., Bespalov V.I., Gerasimov E.B., Gagarin E.S., Mahmudi A., Shein S.G. and others, including the authors of this material, are devoted to the study of approaches to solving issues of ensuring environmental safety of urban areas [1, 2]. The research results show that a large metropolis almost completely changes the natural components: atmospheric air, soil cover, phytocenosis, relief, surface and groundwater, climate [3–5]. There are inextricable links between the elements of urban environment and natural components. Thus, a typical example is a city street, where the anthropogenic elements are buildings, motor transport, road surface; and green spaces and atmospheric air are natural components [6, 7]. Such a connection inevitably leads to a negative impact of elements of the urban environment on natural components, and the spectrum of this impact is so wide that it causes a number of problems characteristic of almost any modern city [8]. To achieve this goal, the authors used methods of comparative and system analysis and generalization. Having summarized and systematized the results of the conducted analytical studies, it was possible to present the totality of the most acute environmental problems of a modern city in the form of a diagram (Fig. 1).

Such a variety of identified problems is primarily due to the peculiarity of urban infrastructure [9, 10]. It includes not only industrial clusters and residential areas with high building density, but also shopping and entertainment complexes, urban facilities and recreational areas. As a whole, all elements of urban environment should provide favorable conditions for the population to live. Simultaneously with providing favorable living conditions, elements of urban environment should not have a negative impact on natural ecosystems. Therefore, the inevitable close interaction of a set of living beings and a highly urbanized environment generates interdependence and forms a special form of the ecosystem — an urbanized one.

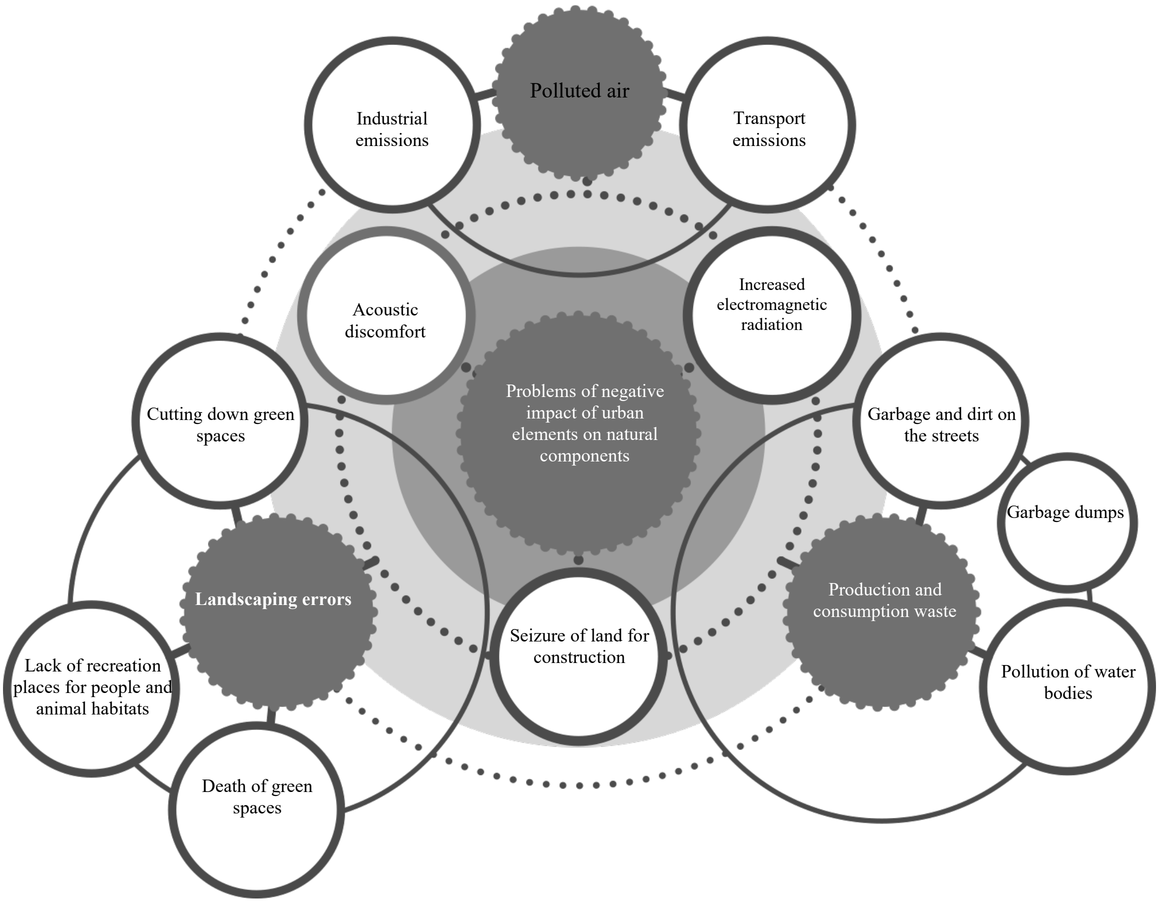

Fig. 1. The problems of negative impact of urban elements on natural components of the environment

It is obvious that the urbanized ecological system constantly consumes external resources and is not capable of self-regulation. Such a system develops not according to the laws of nature, but according to the needs of human economic activity. That is why the approach to solving the problem of ensuring balance in an urbanized ecosystem should be special, taking into account all the parameters of the properties of natural and anthropogenic components of the urban environment.

Results. The concept of "negative factor affecting the urban environment" implies, first of all, the specifics of the process of its impact on the surrounding components, during which the signs of negative change appear. Each process of negative change has its own impact characteristics and is determined by its nature, intensity, and source [11]. However, a comparative analysis of features of the impact of negative factors on the urban environment allowed us to systematize them by the nature of their impact on the natural components of urbanized territories.

The inevitable and, perhaps, the most negative factor in the urban environment is the use of land as a spatial basis for the construction and placement of objects of economic activity. Depending on the nature of use, the land is subject to depletion, preconsolidation, pollution, flooding, etc. The environmental requirements set out in Chapter VII of the Law "On Environmental Protection" regarding the placement of economic activities, their design, construction and reconstruction, as well as commissioning, do not fully ensure equilibrium in the urbanized ecosystem and lead to the above-described consequences.

Widespread pollution of natural components in the process of urbanized ecosystems functioning is associated with the active growth and development of industry, transport systems, construction of energy facilities and, of course, residential space [12, 13]. Of course, the degree of influence of pollution sources varies and depends on the level of improvement of urban neighborhoods and a number of socio-economic factors: legislative, political, demographic, personal and infrastructural [14, 15].

When it comes to the sources of environmental pollution of urbanized territories with chemicals, it can be assumed, that the most significant of them are the facilities and infrastructure of the motor transport complex. With every 15 thousand km, one car burns an average of 2 tons of fuel, about 30 tons of air, including 4–5 tons of oxygen, which is 50 times more than a human needs, while it emits carbon monoxide into the atmospheric air of cities — 700 kg/year, nitrogen dioxide — 40 kg/year, hydrocarbons — 230 liters, solids — 2–5 kg/year [16, 17].

The analysis of the results of long-term observations and studies allowed us to conclude that the greatest contribution to the air pollution of highly urbanized territories was made by cars running on gasoline, to a lesser extent — cars running on diesel fuel, the minimum contribution — cars running on gaseous fuel [1, 2, 8].

Pollution, as a negative factor affecting the urban ecosystem, largely came from industrial facilities, the maximum number of which was concentrated in highly urbanized territories and territories directly adjacent to them [10].

It was established that the main sources of pollution among industrial facilities were [7, 10]:

– at ferrous and non-ferrous metallurgy enterprises — crushing and grinding equipment, places of unloading, loading and pouring of materials, blast furnaces and open-hearth furnaces, installations for continuous casting of metals and others;

– at chemical, petrochemical and oil refining enterprises — technological equipment in the production of acids, rubber products, plastics, dyes and detergents, artificial rubber, mineral fertilizers, various solvents (toluene, acetone, phenol, benzene), in the production of phosphorus;

– at enterprises producing building materials — roasting furnaces, drying drums of various types, lime quenching reactors, crushing and grinding equipment, drying machines, glass furnaces, bitumen melting units, sorting machines, drying units, mixers, power units, etc.

The results of monitoring the quality of environmental components in the territories near the location of the above-mentioned facilities showed that the degree of negative influence of pollutants often exceeded several times the values established by regulations [12]. When it came to pollutants that were prioritized by the level of content in the urban environment atmosphere, special place certainly took carbon monoxide and dioxide, nitrogen and sulfur oxides, aromatic hydrocarbons, solids, including inorganic, with different content of silicon dioxide, compounds of lead, chromium, vanadium, mercury and other chemical elements, organochlorine substances, phenol, benzene and its homologues, formaldehyde, ammonia, benz(a)pyrene, hydrogen sulfide, carbon disulfide, volatile organic compounds, pesticides [13]. All this confirmed the fact of insufficiency or inefficiency of the envisaged organizational, technological and special engineering and environmental measures designed to ensure the ecological safety of the urbanized territory.

Despite active development of the principles of green urbanism, there was still a shortage of green spaces in large cities and the condition of the existing plantings was deteriorating. This was manifested in the violation of production process, deformation and thinning of crown, progression of dryness, as well as necrosis and chlorosis of leaves and needles. Such processes occurred not only due to pollution of components of the urban environment, but also due to a decrease in soil fertility, its compaction and pollution. The authors revealed that these negative factors were particularly intense in areas of multi-storey buildings. Therefore, solving the problem of planting of urbanized neighborhoods, it was necessary to investigate and take into account a whole range of negative factors that depressed vegetation and, as a result, led to the loss of its ecological functions. Green spaces deprived of their qualities were not only useless for ensuring balance in the urban ecosystem, but were also aesthetically difficult to perceive.

Along with the above negative factors, urban environment was subject to the intense influence of various physical fields: acoustic, vibrational, electromagnetic, thermal, radiation [6, 7]. At the same time, acoustic discomfort was created primarily by objects of the transport system: air, rail, road and water transport. Sports and entertainment facilities, industrial cluster and housing facilities, and communal services made a significant contribution to the acoustic pollution of the urbanized environment. Long-term studies also established that urban noise sources created an excess acoustic background, which negatively affected the health of the population living on this territory [5].

As a rule, a negative acoustic background in an urban environment increased the vibration effect from urban rail and road transport. It was known that prolonged regular vibration exposure of living components to the environment led to a change in the habitat of organisms and had a destructive effect on the human central nervous system [14].

Another significant negative factor in a highly urbanized urban environment was the electromagnetic field. The sources could be power supply complexes, extended power transmission lines, thermal power plants and transformer substations, cellular base stations, television complexes, radar installations, and radio stations [15].

Along with the electromagnetic field, the urbanized environment was negatively affected by the thermal field. Excess heat in the urban environment arose from such facilities as thermal power plants, nuclear power plants, boiler houses, heating mains, oil production and processing facilities, metallurgical plants, vehicles, subways, underground heated structures [16].

The most dangerous type of physical pollution in the urban environment was radioactive emission, which did not manifest itself under normal conditions of urban infrastructure development. The risk of this factor occurred during the liquidation of man-made accidents at nuclear power facilities. However, in recent years, much attention has been paid to the issue of ensuring safety of such industrial facilities, so the probability of the appearance of a nuclear radiation factor remains minimal.

The most uncontrolled negative factor in a highly urbanized environment could be considered biological pollution associated with the appearance and spread of pathogenic microorganisms in the atmospheric air, in water bodies or in the soil, leading to the threat of all kinds of changes in the health of the population, an outbreak of epidemics. The main sources of pathogenic microorganisms were the objects of drainage and water supply complexes, public catering facilities, cemeteries, medical and laboratory institutions, agricultural enterprises [17].

The detailed description of the types of negative factors affecting the environment of urban areas presented above showed, on the one hand, the variety of types of impacts, and on the other hand, the need to build relationships and systematize the listed parameters for the possibility of automated work with them.

During the study of the impact of negative factors on the city environment and the subsequent measurement of the ranges of their impact, the authors analyzed the functional zones of a typical urban area in order to identify the sources (objects) of the appearance of such negative factors. The conducted analytical studies showed a wide variety of factors that could negatively affect the environment of highly urbanized territories. The system approach proposed by the authors allowed structuring information, speeding up its analysis and making appropriate decisions in the subsequent selection of environmental measures for each specific case. At the same time, the main principle that guided the authors was the prompt solution to the problem of ensuring the environmental safety of the territory of a construction or landscaping object.

Any task assumes an array of source data, which should provide a complete picture of the intended course of solving the problem. In the situation under consideration, the array of initial data should obviously include such information as the process being implemented, as a result of which it is necessary to ensure environmental safety (construction or operation), the name of the object of research (industrial enterprise, shopping center, hotel, car wash, railway station, etc.), the functional zone in which this object is located (planned), a list of negative factors of the impact of the object in question on environmental components (physical, chemical, biological effects). In this regard, it is advisable to structure this kind of information using the method of an interconnected hierarchy of functional zones and related construction and capital repair facilities with negative factors affecting the territories of the facilities and their parameters (Fig. 2).

With this method, the construction of a multi-level data system using a software package will allow you to visually present a large array of data quite easily. The entire path shown in Figure 2 can be automated by providing an analytical task to a software package. After going through several steps sequentially, the user will be able to quickly come to the goal — to get a set of those negative environmental impact factors that are characteristic of the particular object located in a certain functional area of the city.

The obtained exhaustive set of negative factors allowed us to determine further ways of work: carrying out instrumental measurements to determine the parameters of their impact, followed by a detailed selection of a list of environmental measures, or receiving recommendations on a list of possible measures to reduce the negative impact on environmental components without taking measurements.

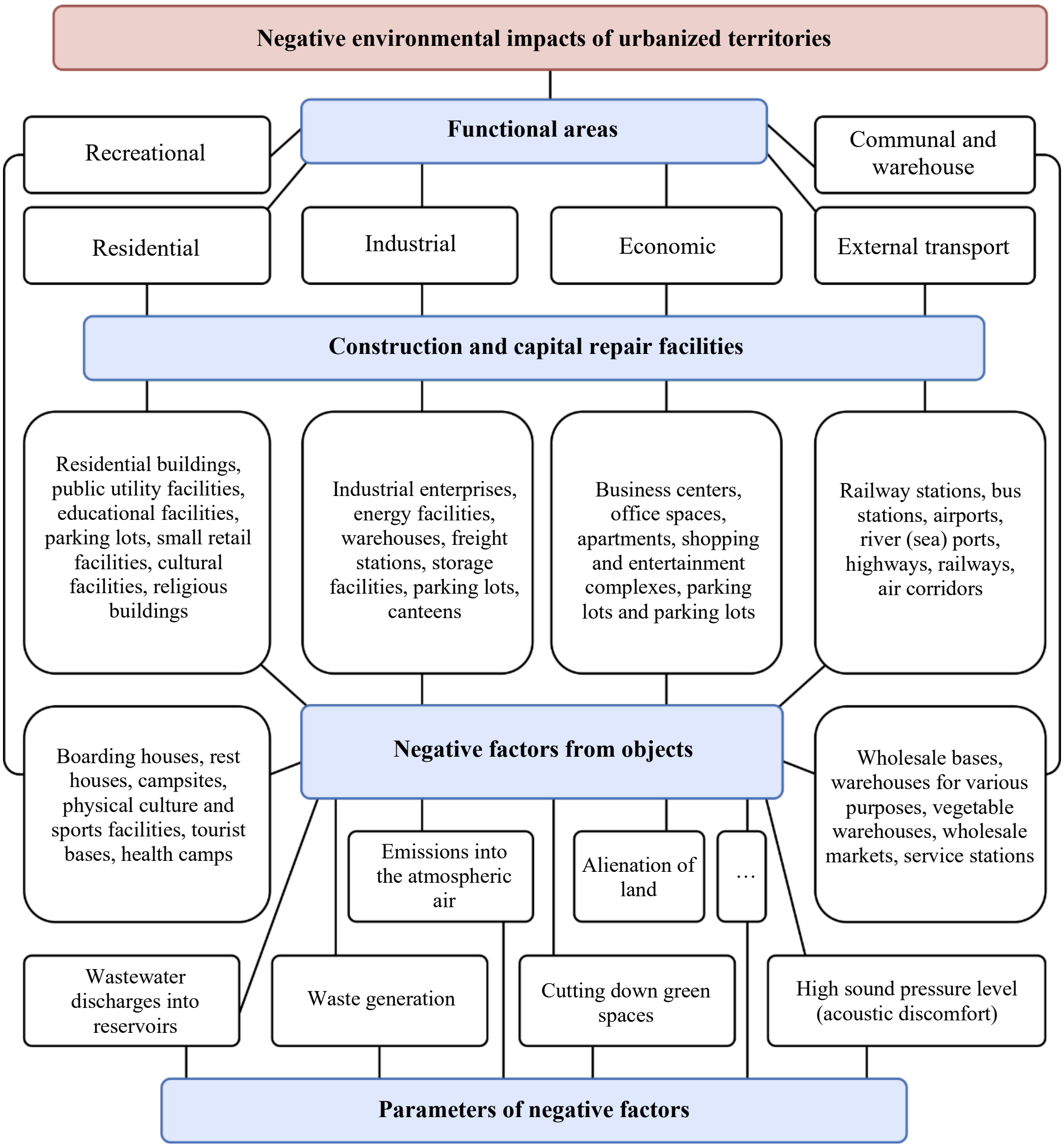

Fig. 2. Systematic approach to the assessment of negative environmental impact of the territories of capital construction and landscaping facilities, depending on the functional zones where they are located

Discussion and Conclusion. Ensuring environmental safety is an important condition for the widespread development of society. Therefore, it is necessary to reduce the negative impact on the environment from various types of human economic activity, including the entire range of construction work. The solution to the problems of ecological safety of urbanized territories is based on a deep analysis of the factors that violate the ecological balance and cause negative consequences in the environment. In modern conditions of electronic products development, the creation of a software package that implements the systematic approach proposed by the authors to determine the negative factors affecting the territories of capital construction and landscaping facilities, taking into account the functional zones where they are located, seems very promising. The generated data array with the information about negative environmental factors from the functioning of various capital construction and urban facilities will optimize the selection of environmental protection measures for each specific case, reducing time costs by automating the process. The introduction and implementation of such measures will contribute to the balanced development of urban environment and improve the quality of life of residents.

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Original article

Analysis of Water Consumption During Fire Extinguishing at Objects of Different Functional Fire Hazard Classes

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Abstract

Introduction. Fire-fighting water supply systems play a primary role in ensuring effective fire extinguishing. Many researchers both in our country and abroad have considered the requirements for fire-fighting water supply and problematic issues in this area. At the same time, in order to update the requirements for fire-fighting water supply, it is necessary to study the actual water consumption on fires, taking into account the characteristics of fire objects. The aim of this research was to analyze the water consumption for outdoor firefighting depending on the characteristics of the fire object and compare the actual water consumption with the requirements of regulatory documents on fire safety.

Methods and Materials. The authors used statistical data on fires in the Russian Federation for 2019–2021 from the federal state information system "Federal Database "Fires". Methods of statistical data analysis and classification of statistical data were used to determine the actual water consumption for outdoor firefighting, depending on the class of functional fire hazard of the fire object. Visualization of the obtained results was performed by the method of graphical representation of data in the form of histograms and pie charts.

Results. The analysis showed that the highest average water consumption was required for objects of the functional fire hazard class F1.2 "hotels, dormitories (with the exception of apartment-type dormitories), dormitory buildings of sanatoriums and rest homes of general type, campsites" — 10.7 l/s. For apartment buildings, the highest average water consumption was required to extinguish fires that had arisen in the attic — 10 l/s and in the garret — 9.2 l/s.

Discussion and Conclusion. The results of the analysis can be used to clarify the requirements for water consumption for outdoor firefighting, depending on the functional fire hazard class of the object and the number of floors of buildings. In order to meet these requirements, regular monitoring of fire-fighting water supply systems is required, as well as timely maintenance and repair of external and internal fire-fighting water supply systems.

Keywords: water consumption, fire, functional fire hazard, building, number of floors

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Научная статья

Анализ расхода воды при тушении пожаров на объектах разных классов функциональной пожарной опасности

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Аннотация
Введение. Системы противопожарного водоснабжения играют первостепенную роль в обеспечении эффективного тушения пожаров. Требования к противопожарному водоснабжению и проблемные вопросы в этой области рассматривались многими исследователями как в нашей стране, так и за рубежом. В то же время для актуализации требований к противопожарному водоснабжению необходимо изучение фактического расхода воды на пожарах с учетом особенностей объектов пожара. Целью настоящего исследования является анализ расхода воды на наружное пожаротушение в зависимости от характеристик объекта пожара и сравнение фактического расхода воды с требованиями нормативных документов по пожарной безопасности.
Методы и материалы. Использованы статистические данные о пожарах в Российской Федерации за 2019–2021 годы, содержащиеся в федеральной государственной информационной системе «Федеральный банк данных «Пожары». Для определения фактического расхода воды на наружное пожаротушение в зависимости от класса функциональной пожарной опасности объекта пожара использованы методы статистического анализа данных и классификации статистических данных. Визуализация полученных результатов выполнена методом графического представления данных в виде гистограмм и круговых диаграмм.
Результаты исследования. Проведенный анализ показал, что наибольший средний расход воды требуется для объектов класса функциональной пожарной опасности Ф1.2 «гостиницы, общежития (за исключением общежитий квартирного типа), спальные корпуса санаториев и домов отдыха общего типа, кемпингов» — 10,7 л/с. Для многоквартирных жилых домов наибольший средний расход воды требуется для тушения пожаров, возникших на чердаке — 10 л/с и в мансарде — 9,2 л/с.
Обсуждение и заключение. Результаты проведенного анализа могут быть использованы для уточнения требований к расходу воды на наружное пожаротушение в зависимости от класса функциональной пожарной опасности объекта и этажности зданий. Для выполнения данных требований необходим регулярный контроль систем противопожарного водоснабжения, а также своевременное обслуживание и ремонт наружных и внутренних водопроводов противопожарного водоснабжения.

Ключевые слова: расход воды, пожар, функциональная пожарная опасность, здание, этажность

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Introduction. The task of determining the required water consumption for outdoor firefighting is of paramount importance to ensure effective actions of operational fire protection units when extinguishing fires. Data on water consumption for outdoor firefighting are used in determining the composition of forces and means of operational fire protection units, drawing up fire extinguishing plans, determining the requirements for outdoor fire water supply systems.

The problems associated with the supply of water to outdoor fire-fighting water supply systems have been considered by many researchers [1–4]. In particular, Zayko V.A., Ilyin N.A., Sargsyan A.M. paid special attention to fire extinguishing organization in small settlements, where, as a rule, there were no fire-fighting water supply systems and the rapid arrival of special fire equipment was not always ensured [5]. Abrosimov Yu.G., Kiselev L.Yu. came to the conclusion that it was necessary to develop new standards and adjust the existing regulatory documents regarding the estimated extinguishing time and water costs for firefighting for cities with a population of more than a million people [6]. Chudakov A.A., Metelkin I.I., Shumilin V.V. analyzed the available information about hydraulic structures intended for fire-fighting purposes [7]. Kalach A.V., Rodin V.A., Sinegubov S.V. considered optimizing the number and distribution of hydrants for outdoor fire-fighting water supply and pumping stations using various metrics measuring distance [8]. Kelishek S., Drzhimala T. considered the main problems related to water supply of fire water supply systems in high residential buildings [9].

Other publications present the results of studies on the reliability of fire-fighting water supply to attract the attention of specialists to this issue [10–13].

Code of Rules SP 8.13130.2020 "The fire protection systems. Outdoor fire-fighting water supply. Fire safety requirements"[1] ((hereinafter — SP 8.13130.2020) defines the requirements for water consumption for outdoor firefighting.

For buildings of functional fire hazard classes (hereinafter referred to as FFH) F1, F2, F3, F4, water supply during fire extinguishing depends on the number of storeys and the building volume and varies from 10 to 35 liters/s per fire. For buildings and structures of F5 FFH class, water supply depends on the degree of fire resistance, on the class of structural fire hazard and on the category of buildings and structures for explosion and fire hazard, as well as on the building volume and ranges from 10 to 100 liters/s per fire.

However, at the same time, there is no specification of the requirements for water consumption for outdoor fire extinguishing for buildings and structures, depending on the FFH classes. The task of the authors was to determine the actual volume of water supply during fire extinguishing, taking into account functional fire hazard classes of fire objects.

Materials and Methods. To determine water consumption when extinguishing fires at various facilities, an analysis of fires that occurred in the Russian Federation in 2019-2021 in the following subjects was carried out: Moscow, Voronezh, Tula, Leningrad, Murmansk, Nizhny Novgorod, Samara, Sverdlovsk, Tyumen regions, Krasnodar, Krasnoyarsk, Primorsky, Stavropol Territories, the Republic of Dagestan, Buryatia, Yamalo-Nenets Autonomous Okrug.

Statistical data on fires and the actual consumption of water for their extinguishing for 2019-2021 were obtained from the fire data bank[2].

Results. Table 1 shows the distribution of fires by water consumption for objects of various FFH classes, defined in accordance with Article 32 of the Technical Regulations on Fire Safety Requirements[3]. Figure 1 provides the distribution of fires by water consumption for all objects. Fires with water consumption of no more than 7 liters/s accounted for 79% of the total number of fires, fires with water consumption of more than 60 liters/s were 0.62%, with water consumption of more than 100 liters/s — 0.18%.

Table 1

Distribution of fires by water consumption depending on functional fire hazard class of the fire object, % of the total number of fires

FFH class	Water consumption, liters/s												Average consumption
	0–3.5	4–7	7.5–12	12.5–20	21–30	31–40	41–60	61–80	81–100	101–120	121–140	> 140	
F1	**47.2**	**33.3**	**10.0**	**6.6**	**2.1**	**0.4**	**0.3**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**6.8**
F1.1	63.9	22.9	4.9	2.8	2.8	0.7	2.1	0.0	0.0	0.0	0.0	0.0	6.6
F1.2	42.3	27.4	11.3	6.9	5.6	1.6	2.8	0.4	1.2	0.4	0.0	0.0	10.7
F1.3	69.8	19.0	4.8	3.9	1.6	0.4	0.3	0.1	0.1	0.0	0.0	0.0	5.7
F1.4	36.2	40.3	12.5	7.9	2.3	0.4	0.2	0.0	0.0	0.0	0.0	0.0	7.3
F2	**43.1**	**28.5**	**12.4**	**7.3**	**7.3**	**0.7**	**0.7**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**8.2**
F2.1	42.0	27.5	14.5	7.2	7.2	0.0	1.4	0.0	0.0	0.0	0.0	0.0	8.4
F2.2	30.0	35.0	15.0	5.0	10.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9
F2.3	47.8	21.7	8.7	17.4	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8
F2.4	52.0	32.0	8.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.7
F3	**51.6**	**30.4**	**7.5**	**6.3**	**2.8**	**0.6**	**0.5**	**0.2**	**0.1**	**0.1**	**0.0**	**0.0**	**7.0**
F3.1	55.0	25.5	7.5	6.7	2.8	0.9	0.9	0.4	0.1	0.1	0.0	0.0	7.4

[1] *The fire protection systems. Outdoor fire-fighting water supply. Fire safety requirements*. Свод правил СП 8.13130.2020. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/565391175 (accessed 14.08.2023)

[2] *O vnesenii izmenenii v Poryadok ucheta pozharov i ikh posledstvii, utverzhdennyi prikazom MChS Rossii ot 21 noyabrya 2008 g. No. 714.* Order of the Ministry of Emergency Situations of Russia of 17.11.2020 No. 848. Information and legal portal Garant.ru. URL: https://www.garant.ru/products/ipo/prime/doc/400020288/ (accessed 14.08.2023)

[3] *Tekhnicheskii reglament o trebovaniyakh pozharnoi bezopasnosti.* Federal Law No. 123-FZ of 22.07.2008. Electronic fund of legal and regulatory documents.URL: https://docs.cntd.ru/document/902111644 (accessed 14.08.2023)

FFH class	Water consumption, liters/s												Average consumption
	0–3.5	4–7	7.5–12	12.5–20	21–30	31–40	41–60	61–80	81–100	101–120	121–140	> 140	
F3.2	50.9	24.2	8.6	9.8	4.0	1.4	0.6	0.4	0.0	0.0	0.0	0.0	7.9
F3.3	62.5	0.0	0.0	37.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.2
F3.4	57.1	36.7	4.1	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	5.5
F3.5	60.7	23.4	7.0	4.9	2.0	0.8	0.8	0.4	0.0	0.0	0.0	0.0	6.6
F3.6	46.9	37.7	7.3	5.3	2.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	6.4
F3.7	43.8	27.1	12.5	10.4	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8
F4	**53.7**	**23.9**	**8.2**	**8.5**	**3.4**	**0.3**	**0.8**	**0.2**	**0.5**	**0.5**	**0.2**	**0.3**	**8.3**
F4.1	55.8	25.7	6.2	8.8	1.8	0.0	0.9	0.0	0.0	0.0	0.0	0.9	8.0
F4.2	69.2	19.2	7.7	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.1
F4.3	52.4	23.7	8.7	8.7	4.0	0.4	0.8	0.2	0.6	0.0	0.2	0.2	8.5
F5	**49.7**	**29.4**	**8.7**	**7.1**	**2.9**	**0.8**	**0.7**	**0.3**	**0.1**	**0.2**	**0.0**	**0.0**	**7.6**
F5.1	40.9	27.9	11.5	10.1	5.5	1.4	1.5	0.7	0.2	0.2	0.1	0.0	9.7
F5.2	53.8	28.4	7.4	6.4	2.3	0.8	0.5	0.3	0.1	0.1	0.0	0.1	7.0
F5.3	46.5	35.8	9.7	5.4	1.6	0.3	0.5	0.1	0.0	0.1	0.1	0.0	6.7
Total	**47.9**	**32.5**	**9.6**	**6.7**	**2.3**	**0.5**	**0.4**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**7.0**

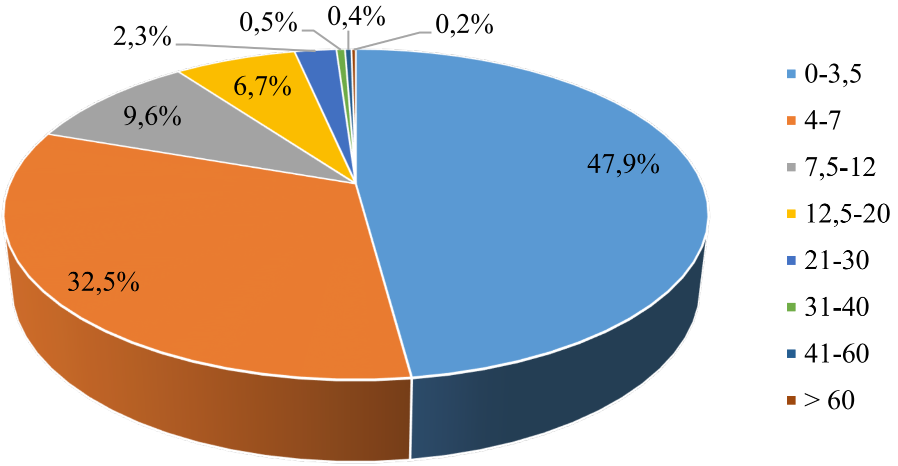

Fig. 1. Distribution of fires depending on water consumption

Figure 2 provides average water consumption during fire extinguishing, depending on the FFH class of fire object. The highest average water consumption was registered for objects of F1.2 FFH class "hotels, dormitories (except for apartment-type dormitories), bedroom buildings of sanatoriums and rest homes of general type, campsites" — 10.7 liters/s. In the second place by the value of the analyzed indicator were objects of F2.2 FFH class "museums, exhibitions, dance halls and other similar institutions in enclosed spaces" — 9.9 liters/s. In the third place — objects of F5.1 FFH class "industrial buildings, structures, production and laboratory facilities, workshops, crematoriums" — 9.7 liters/s.

The lowest average water consumption was registered for objects of F4.2 FFH class "buildings of educational institutions of higher education, organizations of additional professional education" — 5.1 liters/s, objects of F3.4 FFH class "buildings of medical organizations intended for medical activities, except for buildings belonging to F1.1 category" — 5.5 liters/s and objects of F1.3 FFH class "multi-apartment residential buildings, including apartment-type dormitories" — 5.7 liters/s.

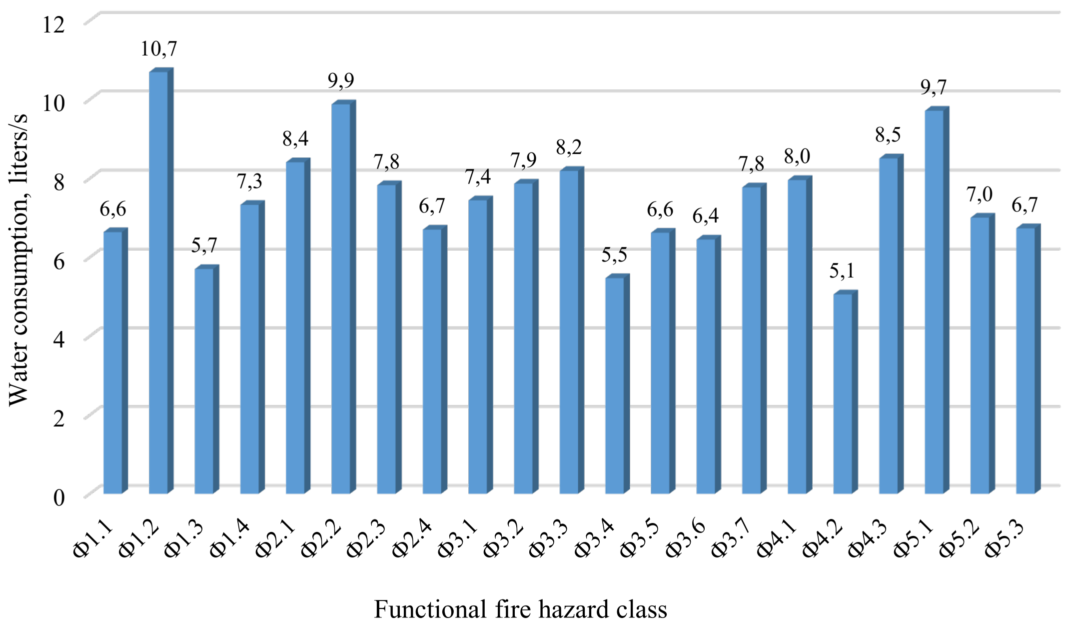

Fig. 2. Average water consumption depending on the functional fire hazard class of the fire object

For objects of F1 FFH class, fires with water consumption of no more than 7 liters/s accounted for 80.5% of the total number of fires; fires with water consumption of more than 60 liters/s were 0.15%, with water consumption of more than 100 liters/s — 0.08%.

For objects of F1.3 FFH class "multi-apartment residential buildings, including apartment-type dormitories", the distribution of fires by water consumption, depending on the floor on which the fire occurred, is shown in Table 2. Fires in apartments and on the premises of shared ownership (basements, mansards, attics) were considered. Figure 3 provides the distribution of fires by water consumption for these objects. Fires with water consumption of no more than 7 liters/s accounted for 88.4% of the total number of fires, fires with water consumption of more than 60 liters/s were 0.25%, with water consumption of more than 100 liters/s — 0.06%.

Table 2

Distribution of fires by water consumption, depending on the floor on which the fire occurred, for objects of F1.3 FFH class "multi-apartment residential buildings, including apartment-type dormitories", % of the total number of fires

Floor	Water consumption, l/s												Average consumption
	0–3.5	4–7	7.5–12	12.5–20	21–30	31–40	41–60	61–80	81–100	101–120	121–140	> 140	
basement	85.4	12.8	0.3	0.7	0.3	0.2	0.3	0.0	0.0	0.0	0.0	0.0	4.3
semibasement	70.3	25.0	0.0	1.6	1.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	5.3
1	64.5	19.7	6.8	5.6	2.1	0.5	0.4	0.2	0.0	0.0	0.0	0.0	6.2
2	67.4	21.2	4.2	3.5	2.1	0.4	0.6	0.2	0.1	0.1	0.0	0.0	6.1
3	76.6	19.4	1.5	1.9	0.4	0.1	0.0	0.1	0.1	0.0	0.0	0.0	4.6
4	78.9	18.0	1.8	0.8	0.2	0.4	0.0	0.1	0.0	0.0	0.0	0.0	4.5
5	81.5	14.9	1.7	1.3	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	4.4
6	77.0	19.7	0.8	2.2	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	4.5
7	77.9	20.0	1.2	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	4.4
8	83.7	13.4	1.5	0.0	0.6	0.3	0.3	0.0	0.0	0.0	0.0	0.3	4.8
9	77.4	18.9	2.3	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4
10	82.7	13.3	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	6.2
11	90.1	5.6	1.4	0.0	1.4	1.4	0.0	0.0	0.0	0.0	0.0	0.0	4.5
12	80.8	19.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.1
13	85.7	9.5	2.4	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2

Floor	Water consumption, l/s												Average consumption
	0–3.5	4–7	7.5–12	12.5–20	21–30	31–40	41–60	61–80	81–100	101–120	121–140	> 140	
basement	85.4	12.8	0.3	0.7	0.3	0.2	0.3	0.0	0.0	0.0	0.0	0.0	4.3
semibasement	70.3	25.0	0.0	1.6	1.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	5.3
14	75.0	22.2	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5
15	85.7	11.4	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0
16	83.8	10.8	2.7	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3
17	89.5	10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8
18–25	84.4	8.9	4.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3
mansard	56.4	3.6	12.7	14.5	10.9	1.8	0.0	0.0	0.0	0.0	0.0	0.0	9.2
attic	44.3	20.3	14.9	9.8	5.7	2.2	1.6	0.6	0.3	0.3	0.0	0.0	10.0
Total	69.3	19.2	4.9	4.0	1.6	0.4	0.3	0.3	0.1	0.0	0.0	0.0	5.7

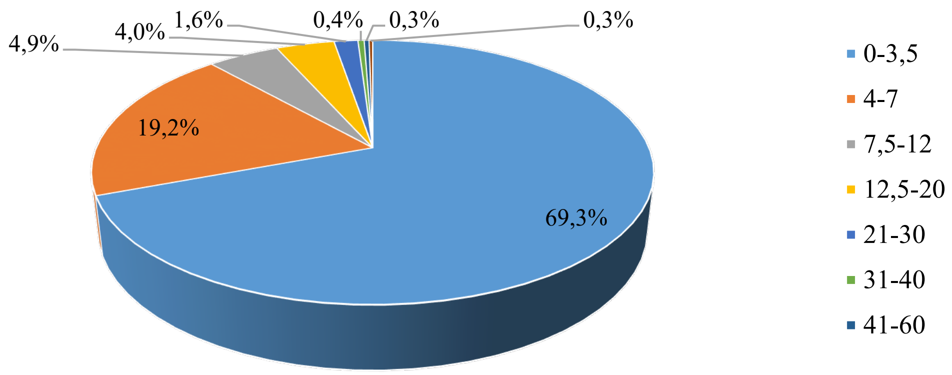

Fig. 3. Distribution of fires on objects of F1.3 FFH class depending on water consumption

Figure 4 provides average water consumption during fire extinguishing, depending on the floor on which the fire occurred, for objects of F1.3 FFH class. The highest average water consumption was registered for fires that occurred in the attic and mansard —10 and 9.2 liters/s respectively, as well as on the first and second floors — 6.2 and 6.1 liters/s. For fires that have arisen on other floors, the average consumption was in the range of 4–5 liters/s. The exception was the 10th floor. For fires on this floor, the average water consumption was 6.2 liters/s. Such a large expense was received due to one fire that occurred on September 30, 2021 in Tyumen at the address: Vostochny Administrative District, Narodnaya str., 10, for the extinguishing of which 15 units of fire equipment were involved and 26 fire-hose barrels were used. The total water consumption was 421 liters/s. With the exception of this fire, the average water consumption for fires on the 10th floor was 4.1 liters/s.

For objects of F2 FFH class, fires with water consumption of no more than 7 liters/s accounted for 71.5% of the total number of fires, fires with water consumption of more than 30 liters/s accounted for 1.46%, fires with water consumption of more than 60 liters/s were not registered during the period under review. The average water consumption at facilities of F2 FFH class was 8.2 liters/s.

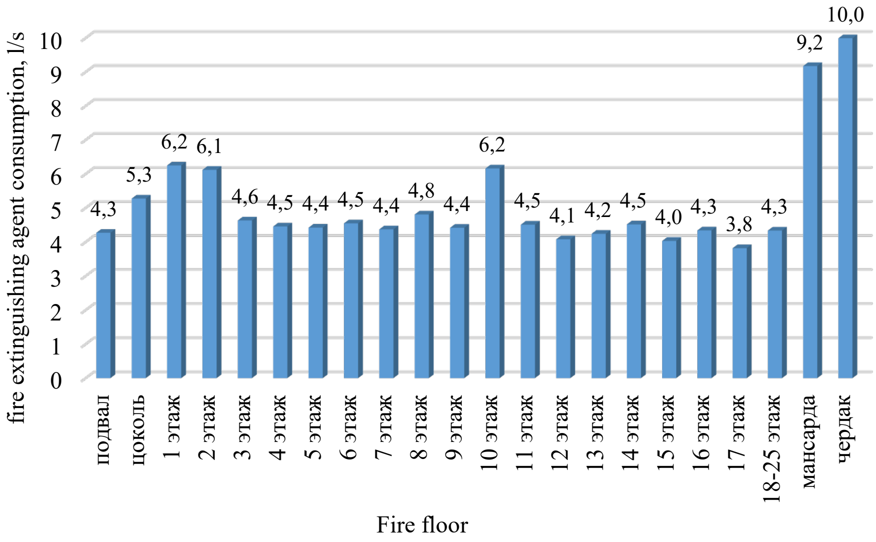

Fig. 4. Average water consumption depending on the floor of fire for objects of F1.3 FFH class

For objects of F3 FFH class, fires with water consumption of no more than 7 liters/s accounted for 81.9% of the total number of fires, fires with water consumption of more than 60 liters/s were 0.38%, with water consumption of more than 100 liters/s — 0.08%. The average water consumption at facilities of F3 FFH class was 7.0 liters/s.

For objects of F4 FFH class, fires with water consumption of no more than 7 liters/s accounted for 77.6% of the total number of fires, fires with water consumption of more than 60 liters/s accounted for 1.13%, with water consumption of more than 100 liters/s — 0.48%. The average water consumption at facilities of F4 FFH class is 8.3 l/s.

Figure 5 provides the distribution of fires by water consumption for objects of F5 FFH class. Fires with water consumption of no more than 7 liters/s accounted for 79.0% of the total number of fires, fires with water consumption of more than 60 liters/s were 0.35%, with water consumption of more than 100 liters/s — 0.18%. The average water consumption at facilities of F5 FFH class was 7.6 liters/s.

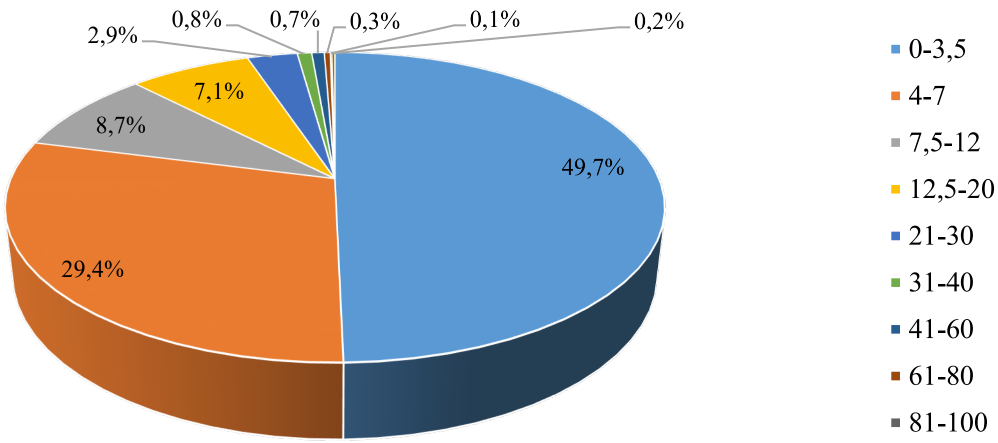

Fig. 5. Distribution of fires on objects of F5 FFH class depending on water consumption

Discussion and Conclusion. A comparison of the results obtained with the standards of SP 8.13130.2020 showed the following.

The actual water consumption per fire for buildings of F1.4 class "single-family residential buildings, including blocked ones" turned out to be higher than for buildings of F1.3 class "multi-apartment residential buildings, including apartment-type dormitories", that is, 7.3 liters/s versus 5.7 liters/s. The maximum water consumption per fire in settlements with low-rise buildings, according to SP 8.13130.2020, was 40 liters/s, while for 29 out of 1000 fires at facilities of F1.4 class, the actual water consumption exceeded 40 liters/s (Table 1).

According to Table 2, water consumption for external fire extinguishing per fire for buildings of F1.3 and F1.4 classes depended on the number of floors of buildings and their construction volume. As studies have shown, the actual water consumption practically did not depend on the floor on which the fire occurred, but increased significantly for fires in attics and mansards floors. At the same time, for buildings with a height of no more than two floors, the SP 8.13130.2020 determines water consumption of 10 liters/s per fire. The actual consumption for 109 out of 1000 fires for buildings of F1.4 class exceeded 12 liters/s.

The scientific novelty of this study consists in the analysis of actual water consumption for outdoor firefighting, depending on functional fire hazard class of the fire object. It is shown that the actual water supply during fire extinguishing differs significantly for different objects — from 5.1 liters/s per fire for objects of F 4.2 class to 10.7 liters/s for objects of F1.2 class.

Thus, the water supply system used for fire-fighting purposes must have a capacity that provides the total amount of water needed to extinguish a fire, that is, when planning fire-fighting water supply pipelines, it is necessary to take into account not only the requirements of SP 8.13130.2020, but also the features of protection facilities.

The results obtained in this work can be used to update the requirements of the code of rules SP 8.13130.2020, which will increase the effectiveness of actions of fire protection units in extinguishing fires.

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Original article

Simulation Modeling of the Process of Accident Risk Realization during Stripping Operations at an Open-Pit Coal Mine

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Abstract
Introduction. The need to increase the level of comprehensive safety, reduce accident and injury rates, minimize the risk of failures, accidents and catastrophes determines the relevance of research on the relationship of elements of the "human–machine–environment" (H–M–E) system during open-pit mining. One of the most effective mechanisms for studying the functional characteristics of the H–M–E system of a coal mine is to conduct simulation modeling in order to identify problematic situations that trigger accidents with catastrophic consequences and injury to personnel. Simulation modeling of a technological process involves constructing a model of a real system and setting up computational experiments to describe the behavior of the system and evaluate various strategies that ensure its functioning. The aim of the research was to adapt simulation modeling technologies to solve the problem of complex safety during open-pit mining. Within the framework of the study, the task was to determine the elements that made the greatest contribution to the implementation of risks in the H–M–E system during stripping operations at a coal mine. The simulated subsystems were "human", "machine", "environment", and "weather conditions".
Materials and Methods. Stripping process was considered in the ARIS eEPC (extended Event Driven Process Chain) methodology as a business process linking a set of subprocesses and/or business operations. To build a simulation model in the AnyLogic software environment, the business process of stripping works in ARIS eEPC notation was described by a graph representing a structure consisting of objects and connections between them. This approach allowed us to structure the sequence of events and operations and determine alternative outcomes that arose during stripping operations.
Results. As part of the research, a method was developed for translating the formal model of the stripping business process in ARIS eEPC notation into a combined simulation model of AnyLogic. Based on the developed method, a series of machine experiments was carried out. The elements influencing the realization of the risk of accidents in the H–M–E system of a coal mine were determined.
Discussion and Conclusion. For the first time in the domestic practice of research of the H–M–E system, simulation modeling technologies have received an application for the analysis of complex safety indicators during open-pit mining. According to the simulation experiment results, it was found that the main influence on the decrease in the reliability of the "machine" subsystem was exerted by the human factor, which, together with the psychophysiological properties of a person, enhanced the development of the domino effect when implementing various types of risks. The presented results and experimental approbation of simulation modeling technology can have advanced use in the analysis of complex technical systems safety, taking into account the influence of human and man-made factors.

Keywords: simulation modeling, “human-machine-environment” system, analysis of risk at an open-pit coal mine, agent-based modeling of overburden face, AnyLogic, eEPC, ARIS

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Научная статья

Имитационное моделирование процесса реализации риска аварии при проведении вскрышных работ на угольном разрезе

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Аннотация
Введение. Необходимость повышения уровня комплексной безопасности, снижения показателей аварийности и травматизма, минимизации риска отказов, аварий и катастроф предопределяет актуальность исследований взаимосвязи элементов системы «человек – машина – среда» («Ч–М–С») при проведении открытых горных работ. Одним из наиболее эффективных механизмов исследования функциональных характеристик системы «Ч–М–С» угольного разреза является проведение имитационного моделирования с целью выявления проблемных ситуаций, являющихся триггерами аварий с катастрофическими последствиями и травмированием персонала. Имитационное моделирование технологического процесса предполагает конструирование модели реальной системы и постановку вычислительных экспериментов для описания поведения системы и оценки различных стратегий, обеспечивающих её функционирование. Целью данного исследования является адаптация технологий имитационного моделирования для решения проблемы комплексной безопасности при проведении открытых горных работ. В рамках исследования поставлена задача определения элементов, вносящих наибольший вклад в реализацию рисков в системе «Ч–М–С» при проведении вскрышных работ на угольном разрезе. В качестве моделируемых подсистем выступают «человек», «машина», «среда», «погодные условия».
Материалы и методы. Процесс вскрышных работ рассмотрен в методологии ARIS eEPC (extended Event Driven Process Chain) как бизнес-процесс, связывающий совокупность подпроцессов и/или бизнес-операций. Для построения имитационной модели в программной среде AnyLogic бизнес-процесс вскрышных работ в нотации ARIS eEPC описан графом, представляющим структуру, состоящую из объектов и связей между ними. Данный подход позволяет структурировать последовательность событий и операций и определить альтернативные исходы, возникающие в процессе выполнения вскрышных работ.
Результаты исследования. В рамках исследования разработан метод трансляции формальной модели бизнес-процесса вскрышных работ в нотации ARIS eEPC в комбинированную имитационную модель AnyLogic. На основе разработанного метода проведена серия машинных экспериментов, определены элементы, оказывающие влияние на реализацию риска аварий в системе «Ч–М–С» угольного разреза.
Обсуждение и заключение. Технологии имитационного моделирования впервые в отечественной практике исследований системы «Ч–М–С» получили приложение для анализа показателей комплексной безопасности при проведении открытых горных работ. По результатам имитационного эксперимента установлено, что основное влияние на снижение надежности подсистемы «машина» оказывает человеческий фактор, который в совокупности с психофизиологическими свойствами человека усиливает развитие эффекта домино при реализации рисков различных типов. Представленные результаты и опытная апробация технологии имитационного моделирования могут иметь расширенное использование при анализе безопасности сложных технических систем с учетом влияния человеческого и техногенного факторов.

Ключевые слова: имитационное моделирование, система «человек – машина – среда», событийный анализ риска на угольном разрезе, агентное моделирование вскрышного забоя, AnyLogic, eEPC, ARIS

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Introduction. During stripping operations at coal mines, the issues of improving safety, reducing accidents, and eliminating cases of injury have always been and still are in the focus of special attention. It is they that give relevance to all research in this field. A modern view on the problem of formation of prerequisites for accidents at a coal mine suggests considering them in the format of the H–M–E system developed in [1, 2]. The system includes an operator-driver of an excavator, a bulldozer, a drilling rig, a dump truck driver (man), a mine excavator, a bulldozer, a drilling rig, a dump truck (machine), a stripping face, a coal face, a drilling unit (working environment). These subsystems interact with each other according to a given technology and the established organization of work within the technological process. In addition to the main components of the system, its model includes connections between them and the surrounding environment, which includes weather conditions, mining and geological factors (rock strength, groundwater level, stability of the side of the section).

Functioning of the H–M–E system is accompanied by the implementation of various types and risk groups that need to be identified in a timely manner and take the necessary measures to protect the system and mitigate the consequences in case of danger. An effective mechanism for investigating functional characteristics of the simulated H–M–E system of a coal mine and identifying problematic situations that trigger accidents with catastrophic consequences and injury to personnel is simulation modeling.

Simulation modeling of a technological process involves constructing a model of the system under study and setting up computational experiments in order to describe its behavior and evaluate (within the limits imposed by some criterion or their combination) various strategies that ensure functioning of this system [3]. Simulation modeling is a key tool for studying the behavior of real systems, though it does not solve optimization problems. It rather represents a technology for evaluating the values of functional characteristics of the simulated system, allowing us to identify its problem areas [4]. Simulation models are widely used in the prediction of logistics systems behavior, design and location of enterprises, optimization of the existing processes, training of personnel, etc.

Currently, there are three main directions in the field of simulation modeling: system dynamics, discrete-event and agent-based modeling. These directions differ in the level of abstraction of the models modeled in their environment. Three levels of simulation modeling abstraction are noted: strategic (high-level strategies that model the behavior of people, organizations), tactical (building models of queuing systems and business process models), operational (building models of mechatronic systems, street and pedestrian traffic, etc.) [5, 6].

The process of stripping operations at a coal mine can be considered in the ARIS eEPC methodology (extended Event Driven Process Chain — extended notation of the description of the process chain) as a description of the flow of sequentially performed works, arranged in the order of their execution [7]. This situation is presented as a business process linking a set of sub-processes, and/or business operations, and/or business functions, during which certain resources are consumed and a product is created (a tangible or intangible result of human labor: an object, a service, a scientific discovery, an idea) that is of value to the consumer [8].

Simulation modeling is carried out in the AnyLogic software environment, which is a flexible multi-agent modeling platform that is used to create a variety of simulation models in the field of business, engineering, logistics and other fields. Various means of specification and analysis of results available in AnyLogic allow us to build models (dynamic, discrete-event, agent-based) that simulate almost any real process, perform computer analysis of models without conducting real experiments and complex computational procedures [9].

Based on the objectives of the study and taking into account the experience of using simulation modeling technology, the following tasks were formulated that should be solved in this work:

1. Describe the process of stripping in eEPC notation.
2. Translate the stripping face model from the eEPC notation into a combined model of AnyLogic software environment; conduct a series of simulation experiments.
3. Compare the results of simulation experiments modeling of the process of risk occurrence and its development into a cause-and-effect sequence of a catastrophic accident and injury to personnel during stripping operations in the H–M-E system of a coal mine.

Materials and Methods. Business process of stripping operations at a coal mine in the eEPC notation [10, 11] can be described by a graph as $G = \{X, V\}$, where X and V are the main components of the model (Fig. 1)

In Figure 1, G (graph) is a structure consisting of objects and links between them. In this context, the graph describes the stripping process and its logical structure. It helps to visualize the sequence of events and operations, as well as to determine what alternative outcomes may arise in the course of work. Figure 2 shows the main types of graph objects used in the construction of the simulation model.

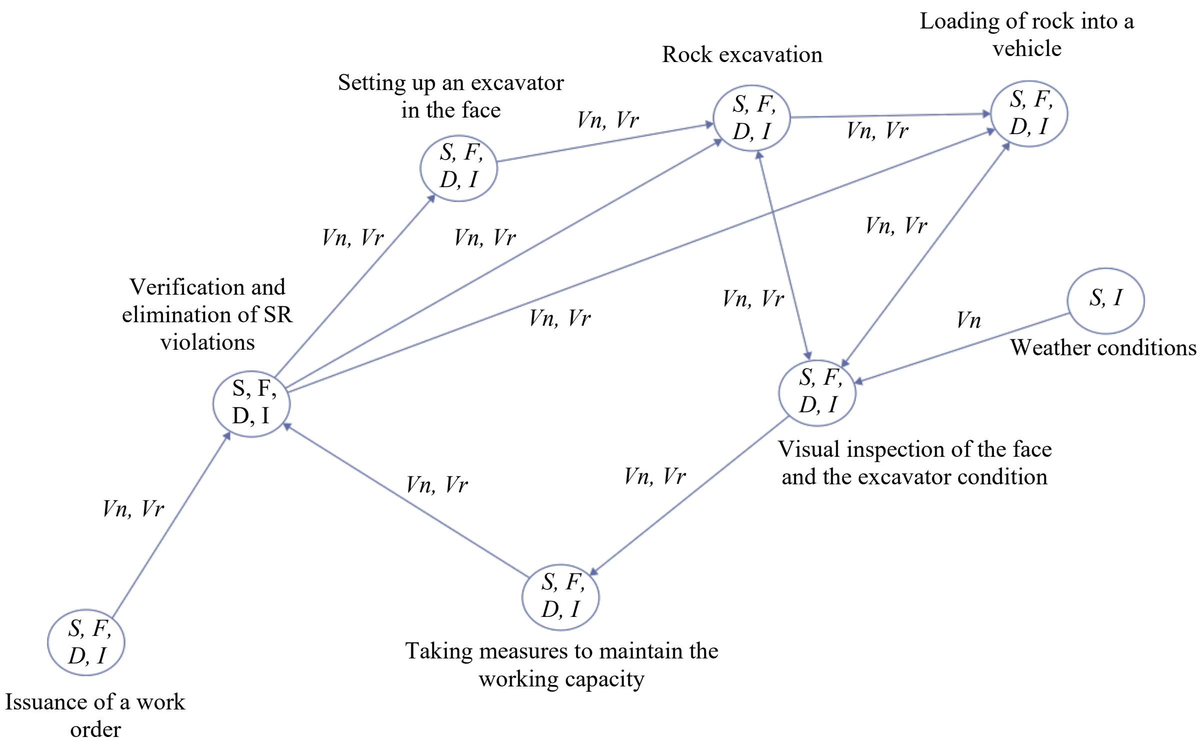


Fig. 1. Graph of the stripping process

1. X — set of model objects (graph vertices), where X = {S, F, D, I} and consists of four types of objects:

• S (events): these objects represent various events or stages that occur during stripping operations, for example, "Setting the excavator in the face", "Rock excavation", "Loading of rock into a vehicle". An example of the implementation of this object in a simulation model is presented by the service block "Beginning of the mining cycle" in Figure 2 *a*.

• F (function): functional objects that can be used during technological operations. These are operations necessary for the successful completion of the process, for example, visual monitoring of the current state of the excavator or the face, monitoring the position of the dump truck and other technological equipment or people in the face. An example of the implementation of this object in a simulation model is presented by the service unit "Visual inspection of the face" in Figure 2 *b*.

• D (operation): operations required to perform stripping operations, for example, technical inspection or repair of an excavator, elimination of violations of safety rules, and so on. An example of the implementation of this object in a simulation model is presented by the service unit "Excavator failure detection" in Figure 2 *c*.

• I (XOR/OR rule): these objects define the logic of branching and merging in the process. The OR rule indicates that after executing several alternative events, the process can continue if at least one of them is completed. For example, a machinist checks the working condition of an excavator at the beginning of a shift. This event can have two outcomes: "technical condition is correct"; "malfunctions have been detected". Both outcomes lead to the realization of different branches of the model development events. The XOR operator means that only one of several alternative ways of developing the model is selected. For example, when an excavator equipment failure is detected by a machinist, the XOR operator sets the probabilities of alternative outcomes: "the working condition of the excavator has been restored", "malfunctions have been identified that do not affect the operation of the excavator", and "operation of the excavator is unsafe". An example of the implementation of this object in the simulation model is presented by the SelectOutput block "Excavator failure type, XOR rule" in Figure 2 *d*.

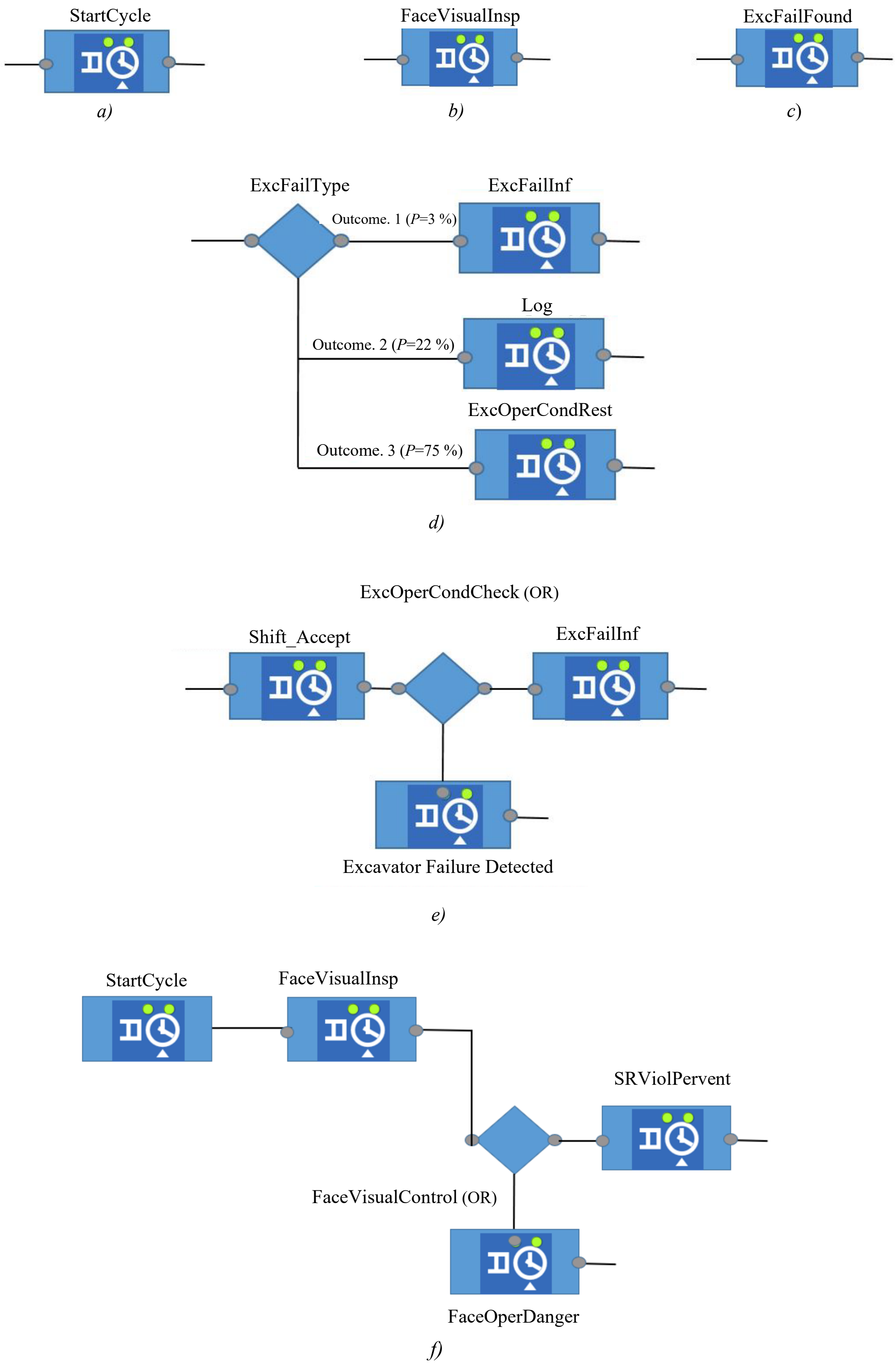


Fig. 2. Diagram of graph objects implementation in the simulation model:
a — "event" (the beginning of the mining and excavation cycle); *b* — "function" (visual inspection of the face); *c* — "operation" (detection of excavator failures); *d* — "XOR rule" (implementation of the type of excavator failure); *e* — "arc" (transition from shift acceptance to checking the working condition of the excavator); *f* — "edge" (alternative ways of branching the further process with visual control of the state of the face)

2. V — the set of arcs and edges that connect objects from the set, that is, the vertices of the graph. V is divided into two subsets:

- Vn (arcs): these relationships between objects indicate a sequence of events or operations. For example, "Shift acceptance" is associated with "Checking the working condition of the excavator", as this is the next step in the process. An example of the implementation of the "arc" in the simulation model is shown in Figure 2 *e*.
- Vr (edges): edges connect vertices with XOR/OR rules, which determine which alternative branching paths may occur in the process. For example, after the start of "Rock excavation" there may be an edge that connects to the OR operator. This means that after the extraction of the rock from the pillar, several different events may occur ("safety violation has been committed", "there is no safety violation"), and the process will continue if at least one of them is completed. An example of the implementation of an edge in a simulation model is shown in Figure 2 *f*.

Agent component of the model in AnyLogic is implemented using the base object — an active object. The active object has parameters, variables that can be considered agent memory, statecharts express behavior: object states and state changes under the influence of events and conditions. The agent in the simulation model of the stripping process is the "Environment" block. The logic of the model provides that the "Environment" influences the magnitude of the driver's error when processing incoming information. In the model, the influence of the "Environment" on the perception of information by the driver is realized by modeling the state of weather conditions. Heavy rain leads to deterioration in visibility from the driver's cab, which may be the reason for incorrect perception of information about the state of the face or the current state of the excavator components. A strong wind raises a cloud of coal dust, which also disrupts visual contact between the driver and the face. Therefore, when the "Environment" does not generate a signal about changes in weather conditions, the probability of a driver's error in 1 hour of work is 94%, when a signal from the "Environment" enters, the probability of an error increases to 96% per hour of work. The generation of changes in weather conditions is carried out randomly.

The Discrete Event Model in AnyLogic is implemented using probability distribution functions and can be described as $\mathrm{ALM} = \{\mathrm{Oper}, \mathrm{Var}\}$. Such a model is used when events occur at discrete points in time and can affect the course of the process, and allows you to model and analyze the stripping process taking into account random factors and variability.

1. Oper — a set of event transition objects between operations performed, includes the following elements:

- Source: a place where events begin or are created, for example, the beginning of the production of works by the excavator operator after receiving the work order;
- SelectOutput: a mechanism that determines where an event will be directed after it has occurred. For example, after the driver has completed visual inspection of the condition of the face, SelectOutput will help determine which action will be the following one: continue work or proceed to the elimination of industrial safety violations in the face.

2. Var — a set of variables that are used in the model to store data or process state. For example, these are variables that track the execution time of each operation or event.

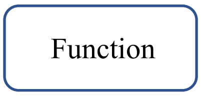
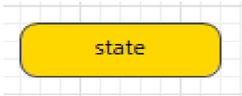
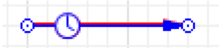
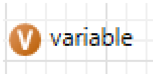
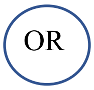
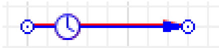
The interaction of the elements of the proposed model in the process of occurrence and realization of risk is discussed below on the example of performing a technological operation for excavating rock from an overburden by a driver of a hydraulic quarry excavator. The aim of conducting an experiment on simulation modeling of the process of stripping operations at a coal mine in the ARIS eEPC notation was to determine which of the subsystems ("human", "machine", "environment") makes the most significant contribution to the causal chain of prerequisites for the implementation of risk in the H–M–E system

Results. The simulation modeling method is applicable for a priori assessment of the possibility of risk realization and its development into technogenic accidents. At the same time, the requirement for the mass and stochasticity of the process under study is observed, which allows the use of simulation modeling to predict the implementation of risk and accident and injury parameters.

At the first stage of the modeling process, the stripping face model from the eEPC notation is translated into a combined model of the AnyLogic software environment, which allows you to determine the probabilities of events in the XOR and OR branching rules. Based on the proposed method, a model is built in AnyLogic. After obtaining the structure of the combined simulation model, the numerical characteristics of the model objects necessary for simulation modeling are determined: indicators for eEPC functions (work completion time), the number of performers (organizational units), probabilities of events in the branching rules, probabilities for XOR and OR. A description of the correspondence of objects of eEPC notation model and elements of the combined simulation model in the AnyLogic language is given in Table 1.

Table 1

Description of the correspondence of objects of eEPC notation model and elements of combined simulation model in the AnyLogic language

Object of the eEPC model	Graphic designation	Corresponding AnyLogic element	Description of the AnyLogic element
Function $F \in X \in G$		State $S_t \in S_{ch} \in A \in ABM$ 	Simple state of the statechart (state diagrams)
Initial Event $S_s \in S \in X \in G$		Transition $T_{rn} \in S_{ch} \in A \in ABM$ 	Transition from the hyperstate of the statechart to a simple state. It can also be determined by the timer set by the analyst
Event S_m, $Sf \in S \in X \in G$			
Material resources			
Operation (Product/ Service) $P \in X \in G$		Variable $Var \in E \in ABM$ 	Variables are used to model changing characteristics to store simulation results. The change in quantitative resources occurs in the state of the statechart, it is programmed in the Java language
Branching rules			
OR rule $R_{or} \in R \in X \in G$		Transition $T_{rn} \in S_{ch} \in A \in ABM$ 	When switching from a simple state of the statechart to a hyperstate, the Action transition method in Java programs the logic of the agent's decision-making
XOR rule $R_{xor} \in R \in X \in G$			

As a prototype of agents, combinations of eEPC operations are used, which are performed in each of the subsystems "human", "machine", "environment". The behavior of agents is realized by the modules "operation", "function", and "event". The transition between operations is carried out with a time delay, which is determined stochastically, that is, each simple operation is given a time delay for transmitting a signal to the next operation. This delay is described by the probability distribution function corresponding to this operation. The probabilistic logic of XOR and OR branching rules is implemented during the transition between operations and is programmed in the corresponding stochastic nodes of the model.

For technological operations of the stripping process, the probability distribution function of its execution time is determined based on the following indicators:

– statistical data obtained from the results of time study observations;

– calculated parameters (calculation of time intervals of operations based on statistical data);

– expert judgments. In the absence of statistical data, the expert value of the time distribution function of operations or the probability of an event for a stochastic node was assumed. An example of choosing a probability distribution function for a simulation model is given in Table 2.

Table 2

Example of choosing a probability distribution function

Event	Probability distribution function	Logic of choosing a distribution function
Discrete transitions from shift acceptance to the start of the mining and excavation cycle. Transition intervals between operations are expressed in time units, min., hour		
Checking the technical readiness of the excavator, min.	Unform (3, 7)	Time interval is chosen based on timing
Perception and processing of information by the machinist during the cycle of excavation and loading operations. The intervals of transitions between operations are expressed in time units, s.		
Visual control of the state of the face, min.	Unform (1, 3)	Time interval is chosen based on timing
Realization of risk when performing stripping operations. Transition intervals between operations are expressed in time units, sec., min.		
Actuation of the excavator protection for the ball valve, s.	Exponential (166.67, 0.005)	Expert assessment Opening time of the safety valve is considered as a random event. The opening time of the safety valve is a random variable with an average value (mathematical expectation) μ, the probability density function of the exponential distribution has the form f(x) = λ * exp(-λx), where x — opening time of the valves, λ = 1/μ — intensity parameter. The opening time of the safety valve (x) is from 5 to 15 ms. at the speed of movement of the locking piece from 10 to 30 cm/s. The ball and conical valves have the highest speed, which are triggered in 6 and 8 ms., respectively. For the safety valve, the limitation of the response time within 0.9 seconds is taken into account to avoid failure of the actuating element. The value of λ (intensity) calculated as the inverse of the opening time: for a ball valve: λ = 166.67 ms., for a conical valve: λ = 125 ms.
Probabilities of occurrence of events in the branching rule XOR and OR		
Accuracy of the reaction of the driver	Output true: Gamma (1, 1.42857142857, 0.7)	Expert assessment For modeling, we use the gamma distribution, since it allows us to determine the probabilities of the duration of time before a certain event, i.e. the reaction of the driver to deviations in extreme conditions. X = 0.7 — hidden reaction time + processing of a unit of information = 42 s. or 0.7 min. Since there are no statistical data or expert estimates, the assumed values for the parameters are accepted α = 1 and β = 1/x=1/0.7=1.42857142857 (the inverse value of the minimum reaction time)

The "Environment" agent behavior is set by a state diagram (Java code that randomly generates weather changes: rain or wind). The simple conditions of the state diagram correspond to the eEPC functions. The agent state diagram consists of several simple states that the agent enters after each function is performed. The probabilistic logic of the XOR and OR branching rules is implemented in the Java Action transition method when changing states.

Figure 3 provides the page for launching the simulation model in AnyLogic. When initiating a simple experiment in the AnyLogic environment, the model starts with the specified parameter values, supports time mode, animation and debugging of the model. Before starting the launch, you need to select the start date of the experiment, time and number of drivers in the shift. The number of drivers in a shift by default is equal to the number of faces and the number of excavators in a shift.

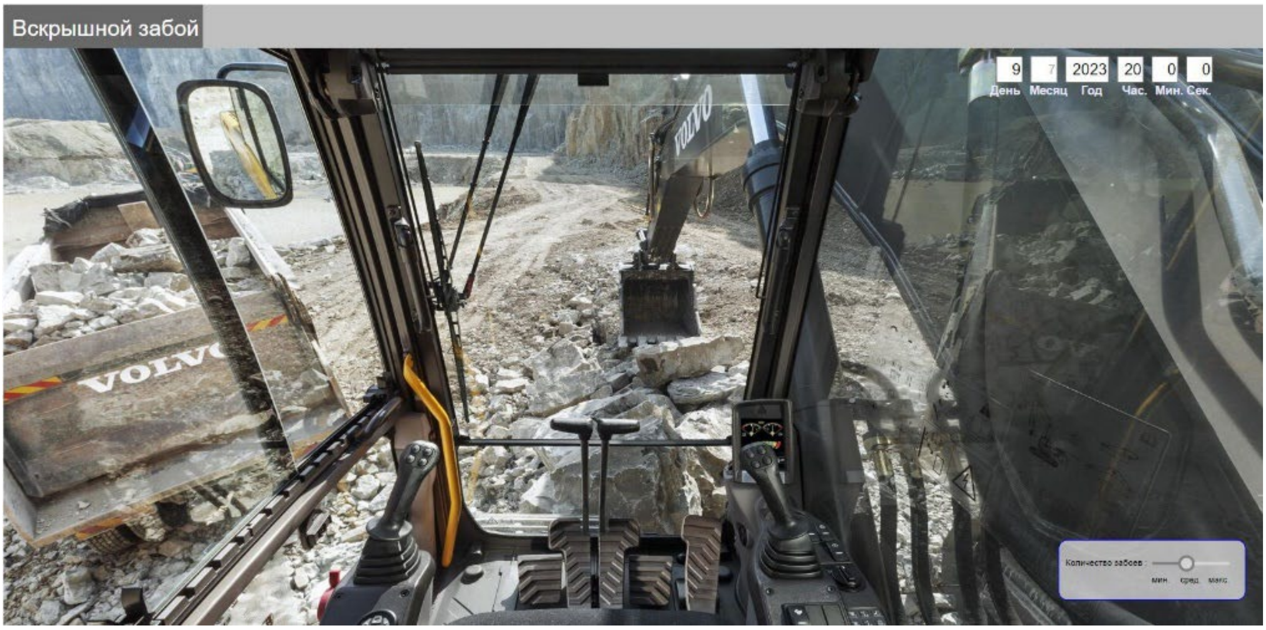


Fig. 3. Launch page for the simulation of the combined simulation model of the stripping face

Figure 4 provides a fragment of the model (shift acceptance) based on the eEPC model, its active objects and environment. Active objects are entities that can perform actions, change their state and interact with each other inside the model. They are elements that have their own behavior and can affect other objects and elements of the model. An environment is an area in which active objects perform their actions, move and interact with each other (for example, a physical space — a stripping face, an excavator cabin). In a discrete-event environment, active objects process events, change their state, and interact through event queues.

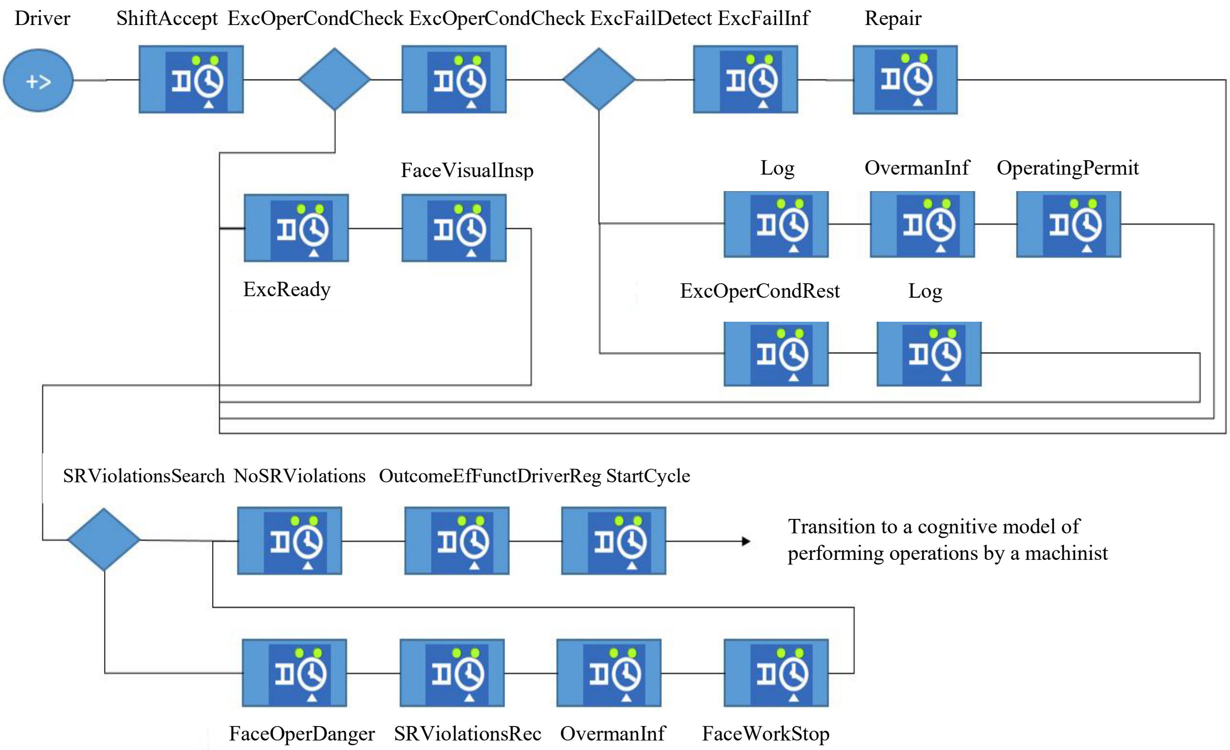


Fig. 4. Active objects and their environment in the AnyLogic combined simulation model

Tables 3–9 present the comparison results of the data of modeling the process of risk occurrence and its development into a cause-and-effect sequence of a catastrophic accident and injury to personnel in the H–M–E system of the coal mine. Simulation studies in the AnyLogic system were carried out for the same model period of time (11 model hours — shift duration) and with the same input data (with 10 experimental identical runs of the model). In each of the experiments, the number of machinists, excavators and faces was five per shift.

Table 3

Statistics of reliability indicators of the "machine" and "environment" subsystem in the H–M–E system of the coal mine during shift acceptance, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
"Environment" subsystem											
Operation of the face is unsafe	11	5	10	6	15	13	13	16	13	24	13
Operation of the face is safe	89	95	90	92	85	87	87	84	88	76	87
"Machine" subsystem											
Emergency failure	–	–	–	–	–	–	–	–	–	–	–
Complex malfunctions	–	–	–	–	–	–	–	–	–	–	–
Troubleshooting issues	–	100	–	–	100	–	–	–	100	–	100
Operation time	100	100	100	100	100	100	100	100	100	100	100
Repair time	–	–		–	–	–		–	–	–	–

At the acceptance of the shift by the drivers, the malfunctions that could be eliminated were detected, which did not affect the unplanned downtime of the excavators, as a result of which the excavators were in operation all the time.

In 87% of cases, when accepting a shift, the drivers did not detect violations of the requirements of the rules of industrial safety in the face. In 13% of cases, violations were detected, which led to the downtime of the stripping face "until the violations were eliminated".

Table 4

Statistics of the reasons for reliability decrease of the subsystems "machine", "environment" when performing a cycle of excavation and loading operations, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
"Environment" subsystem											
Violations on the human factor	46	61	52	67	53	60	64	65	56	48	57
Violations due to the unsatisfactory state of the external environment	54	39	48	33	47	40	36	35	44	52	43
"Machine" subsystem											
Failures during operation	21	9	25	31	18	24	16	17	25	20	21
Failures due to poor organization of work	79	91	75	69	82	76	84	83	75	80	79

During the cycle of excavation and loading operations, at visual inspection by the machinists, deviations in the operation of the excavator were detected and local violations of industrial safety requirements in the overburden were allowed. About 57% of the violations in the face were due to the human factor, which was due to the insufficiently efficient organization of the operating personnel work (lack of proper control by the line engineers and technicians, suspension of work due to violations). Similarly, the insufficiently effective organization of work affected the failures of the excavator during the execution of work (failure to carry out scheduled repairs, run-to-failure).

Table 5

Statistics of the driver's reaction to the loss of the dynamic equilibrium of the H–M–E system, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
Complete elimination of the deviation	44	46	42	55	56	56	55	63	46	49	51
Partial elimination of the deviation	24	26	32	22	25	27	18	20	22	30	25
The deviation cannot be eliminated	32	28	26	22	19	17	27	17	32	21	24

During the realization of emergencies, in 51% of cases, the drivers completely eliminated deviations from the normal operating mode of the excavator and the face. At the same time, the proportion of partially eliminated violations and violations that could not be eliminated was approximately the same.

In the rows of Table 6, statistics on the actions of the driver in case of violation of the dynamic equilibrium of the system are presented in fractions according to the following scenarios: 1 — "partial elimination of the deviations occurred", 2 — "deviations cannot be eliminated".

Table 6

Statistics of the driver's actions to the loss of the dynamic equilibrium of the H–M–E system, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
Precise action	–/–	7/10	10/–	–/1	–/–	9/14	8/–	7/–	7/5	–/–	8/7
Erroneous action	100/100	93/90	90/100	17/16	96/100	91/86	92/100	93/100	93/91	100/100	86/88
Inaction	–/–	–/–	–/–	–/–	6/–	–/–	–/–	–/–	–/5	–/–	6/5

With partial elimination of the deviation in 86% of cases, the attempts of the drivers to stabilize the operation of the H–M–E system were erroneous and only 8% were successful. As a result, erroneous actions led to an increase in the proportion of deviations that could not be eliminated.

Table 7

Statistics of alternative outcomes of the model, %

Experiment no./ type of outcome	1	2	3	4	5	6	7	8	9	10	Average
Adverse environmental effects	24	22	23	16	24	24	20	19	26	30	23
Excavator failure	12	4	14	16	8	11	7	9	10	7	10
Inefficient organization of work	43	41	38	32	40	38	42	41	28	35	38
Operating personnel	22	33	25	36	28	27	31	31	36	28	30

Most often, the combined model realized alternative outcomes associated with inefficient organization of work and operating personnel. Thus, the human factor was the main reason for the loss of dynamic equilibrium by the H–M–E system during the stripping face simulation.

Table 8

Statistics on the risk type realization in the H–M–E system of the open-pit coal mine, %

Experiment no./ type of outcome	1	2	3	4	5	6	7	8	9	10	Average
Dangerous mistake	53	55	33	61	55	61	55	48	46	68	53
Dangerous failure	45	40	61	36	39	39	42	48	49	32	43
Operating personnel	3	5	6	3	6	0	3	4	6	–	4

According to statistics, the risk associated with the assumption of a dangerous mistake by machinists during stripping operations was most often realized; its share was 53%. The share of dangerous excavator failure accounted for 43% of cases, operating personnel — 4%. Thus, the trigger for the development of risk was the human factor due to the insufficiently effective organization of work. The effect of the human factor was amplified by the error of the driver in the process of work, which could lead to a domino effect when risks were realized.

In the rows of Table 9, the results of modeling the three outcomes of the experiment in the realization of risk are presented through a fraction: 1 — "dangerous error", 2 — "dangerous failure", 3 — "uncalculated external influence".

Table 9

Statistics of experiment outcomes in the realization of risk in three scenarios, number of cases

Experiment no./ type of outcome	1	2	3	4	5	6	7	8	9	10	Total
Dangerous situations have occurred	20/ 17/ 1	29/ 21/ 3	12/ 22/ 2	20/ 12/ 1	17/ 12/ 2	20/ 13/ –	17/ 13/ 1	12/ 12/ 1	16/ 17/ 2	15/ 7/ –	178/ 146/ 13
Dangerous situations have been eliminated	19/ 17/ 1	26/ 18/ 3	12/ 21/ 1	17/ 12/ 1	16/ 10/ 1	20/ 13/ –	16/ 12/ 1	9/ 10/ 1	16/ 16/ 2	14/ 6/ –	165/ 135/ 11
"Human" subsystem failure	–/ –/ –	1/ 1/ –	–/ 1/ –	3/ –/ –	–/ –/ 1	–/ –/ –	–/ 1/ –	1/ –/ –	–/ –/ –	–/ –/ –	5/ 3/ 1
Catastrophe	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –
Incident, accident, failure	–/ –/ –	1/ 1/ –	–/ 1/ –	3/ –/ –	–/ –/ 1	–/ –/ –	–/ 1/ –	1/ –/ –	–/ –/ –	–/ –/ –	5/ 3/ 1
Injury to personnel	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –
"Machine" subsystem failure	1/ –/ –	2/ 2/ –	–/ –/ 1	–/ –/ –	1/ 2/ –	–/ –/ –	1/ –/ –	2/ 2/ –	–/ 1/ –	1/ 1/ –	8/ 8/ 1
Catastrophe	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –
Incident, accident, failure	1/ –/ –	2/ 2/ –	–/ –/ 1	–/ –/ –	1/ 2/ –	–/ –/ –	1/ –/ –	2/ 2/ –	–/ 1/ –	1/ 1/ –	8/ 8/ 1
Injury to personnel	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –

Analyzing the results of modeling the outcome of "Dangerous error" risk, we can conclude that in 93% of cases the system was able to bring to dynamic equilibrium due to the activation of the excavator protection and the precise reaction of the driver. Nevertheless, the protection of the excavator failed more often, as a result of which the "machine" subsystem had a greater impact on the implementation of this risk. In turn, the failure of the excavator protection may occur due to untimely scheduled repairs or failure to carry out scheduled inspections of the operation of regular protections and locks of the excavator, which was a consequence of the human factor.

When implementing the outcome of the risk of "Dangerous Failure", it was possible to bring the system into dynamic equilibrium in 92% of cases. At the same time, failures of the "machine" subsystem also constituted the main cause of the occurrence of a risky event "Incident/accident/refusal".

When implementing the outcome of the risk of "Uncalculated external influence", it was possible to bring the system into dynamic equilibrium in 85% of cases. At the same time, one failure was registered for the "man" subsystem and the "machine" subsystem.

Discussion and Conclusion. Based on the results of simulation experiments on modeling the process of risk occurrence and its development into a causal chain of a catastrophic accident and injury to personnel in the H–M–E system of the coal mine, it was concluded that the most significant contribution to the prerequisites for the realization of risk in the H–M–E system was made by the "man" subsystem. Despite the fact that when implementing the outcomes of "Dangerous failure" and "Dangerous error", the risks of "Incident/accident/failure" occurred due to a decrease in the reliability of the "machine" subsystem, they were caused by the actions or inaction of personnel, that is, the human factor.

The decrease in the reliability of the "environment" subsystem, according to the results of the simulation experiment, was 57% due to the human factor (intentional deviations from the work project, the admission of violations in the race for volumes). And only 43% was due to the consequences of the unsatisfactory state of the face. In turn, the unsatisfactory condition of the face was a consequence of low performance discipline of the machinist in combination with insufficiently effective production control by line engineers and technicians.

The decrease in the reliability of the "machine" subsystem was also a consequence of the influence of the human factor, since failures of mining equipment in 79% of cases occurred due to insufficiently efficient organization of work, which led to an increase in unplanned downtime of the main technological equipment.

It should also be noted that during the simulation experiments, there were no realizations of the risk of accidents with catastrophic consequences and injury to personnel during stripping operations. The following conclusions can be drawn from this fact:

1. Safety and control measures applied during stripping operations are effective and prevent the occurrence of serious accidents or injuries successfully.
2. A safety model or methodology of work was used, which demonstrated high efficiency in preventing potentially dangerous situations.
3. The results of the experiments indicated competent training of personnel in the rules of safe performance of stripping operations and strict compliance with the established procedures.
4. The absence of cases of injury to personnel indicated that all systems and equipment were functioning at a level that kept the risk of injury at the maximum permissible values.

At the same time, it should be emphasized that the absolute absence of accidents and injuries to personnel during the run of the simulation model does not guarantee complete safety of future operations. In order to confirm the results of simulation experiments and further ensure safety, it is recommended to conduct a systematic risk assessment, analyze previous incidents and constantly improve mechanisms and procedures aimed at maintaining/improving the level of safety at the coal mine.

Simulation modeling technologies for the first time in the domestic practice of research of the H–M–E system have received an application for the analysis of complex safety indicators during open-pit mining. The presented results and testing of simulation technology can be widely used in the analysis of safety of complex technical systems, taking into account the influence of human and technogenic factors.

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Original article

Ensuring Safety of Gas Field Infrastructure Using ALARP and a Systematic Approach

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Abstract

Introduction. A significant part of the global and state economy is the production and supply of hydrocarbon raw materials. The issues of safety in this area will remain important in the coming decades. The problem is actively discussed in the professional and scientific community. Theoretical and applied works are published. Local, point-based methods are calculated and implemented, which allow predicting and preventing emergencies in certain units of the considered objects. At the same time, there are no sufficiently justified and reproducible system solutions that can take into account the state of, for example, oil or gas field as a single complex and act as indicators not only of ordinary local accidents, but also of systemic accidents — catastrophes. Such a scientifically and experimentally based solution is described in this article. The approach is proposed as part of the formation of a comprehensive scientific and technical program (CSTP) to ensure the safety of natural and technogenic objects (NTO). The aim of this work was to describe the practice of its application in the conditions of specific gas fields and to justify the refusal to focus on solutions that took into account only the minimum practically acceptable risk, that is, built on the ALARP principle (as low as reasonably practicable).

Materials and Methods. The article was based on the results of field tests of natural and technogenic objects (NTO) of the oil and gas complex — the Yuzhno-Russkoye field of OJSC Severneftegazprom (SNGP), LLC Gazprom Dobycha Yamburg (GDYA) and the gas pumping station (GPS) Orlovka-2 (Ukraine), conducted with the authors' participation. Significant results were obtained and evidence-based physically interpreted during acceptance tests of an explosion-proof certified, created under the guidance of the authors of a prototype of a disaster response system (DRS) at the integrated gas treatment plant (IGTP) in LLC GDYA in 2006. At the same time, for the first time in the world practice, the fact of early detection and parrying without consequences by means of DRS on the UKPG-2 of the development of a large-scale general industrial disaster was confirmed.

In the form of graphs, the revealed patterns of NTO have been visualized, which made it possible to form harbingers of the development of accidents and catastrophes at the NTO of LLC "GDYA", SNGP and GPS "Orlovka-2". Information on the high experimental reproducibility of the obtained results was presented.

The technology has been developed of early detection and parrying of all types of potentially dangerous self-exciting systemic phenomena on real NTO infrastructure — self-oscillations. Three cases of their excitation in real gas fields were presented.

Results. The paper shows the fragmentary nature and locality of emergency protection systems based on the ALARP principle. The consequence of this was its complete unsuitability for early detection and counteraction to the most large-scale and costly system accidents — catastrophes that were multifactorial processes, in which none of the factors was decisive. The alternative complex solution of the problem proposed by the authors and brought to working condition was based on a system approach adapted to the NTO of the oil and gas complex.

The measured parameters of various NTO infrastructure — fields of LLC "GDYA" and SNGP were processed and analyzed at the moments of development of self-oscillating modes on them, due to self-sustaining nonlinear mechanisms of interaction of NTO elements with constant (non-oscillatory) sources of energy replenishment. Three such modes of self-excitation were illustrated. The most informative in this case were the transient modes of operation of the equipment.

According to the technologies experimentally developed by the authors, the areas of critical operating modes of equipment with pronounced potentially dangerous bifurcation points were analyzed. The result of superimposing treatments of the measured parameters of eight full-scale tests of NTO — graphs of dimensionless amplitude-frequency characteristics of the interconnections of a real dynamic system was presented: "input — gas cooling housing" → "output — pipe casing" at the frequency of self-oscillations.

Discussion and Conclusion. The capabilities of ALARP did not meet the tasks of system monitoring of the occurrence and development of dangerous incidents in gas fields. This conclusion can be attributed to all standard sizes of NTO infrastructure in Russia. Fundamentally different solutions should be used to ensure comprehensive observability, controllability, and safety of NTO. A comprehensive scientific and technical program is recommended: "Innovative hardware and software tools and technologies to ensure the observability, controllability, and safety of the NTO infrastructure of Russia".

Keywords: natural-technogenic object, ALARP principle, safety of oil and gas fields, development of a system accident, counteraction to the development of accidents

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Научная статья

Обеспечение безопасности инфраструктуры газовых месторождений средствами ALARP и системного подхода

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Аннотация

Введение. Значимую часть мировой и государственной экономики составляет добыча и поставка углеводородного сырья. Актуальность вопросов безопасности в этой сфере сохранится в течение ближайших десятилетий. Проблема активно обсуждается в профессиональном и научном сообществе. Публикуются теоретические и прикладные работы. Просчитываются и внедряются локальные, точечные методы, которые позволяют предсказывать и предупреждать аварийные ситуации в определенных узлах рассматриваемых объектов. При этом нет достаточно обоснованных и воспроизводимых системных решений, способных учитывать состояние, например, нефтяного или газового промысла как единого комплекса и выступать индикаторами не только обычных локальных аварий, но и системных аварий — катастроф. Такое научно и экспериментально обоснованное решение описано в представленной статье. Подход предложен в рамках формирования комплексной научно-технической программы (КНТП) обеспечения безопасности природно-техногенных объектов (ПТО). Цель работы — описать практику его применения в условиях конкретных газовых промыслов и обосновать отказ от ориентации на решения, учитывающие только минимальный практически приемлемый риск, то есть построенные по принципу ALARP (англ. as low as reasonably practicable).

Материалы и методы. Исходными для статьи стали результаты проведенных с участием авторов натурных испытаний природно-техногенных объектов (ПТО) нефтегазового комплекса — Южно-Русского месторождения ОАО «Севернефтегазпром» (СНГП), ООО «Газпром добыча Ямбург» («ГДЯ») и газоперекачивающей станции (ГПА) «Орловка-2» (Украина). Значимые результаты получены и доказательно физически интерпретированы при приемо-сдаточных испытаниях сертифицированного на взрывобезопасность, созданного под руководством авторов прототипа системы противодействия развитию катастроф (СПРК) на установке комплексной подготовки газа (УКПГ) в ООО «ГДЯ в 2006 году. При этом впервые в мировой практике был актирован факт раннего обнаружения и парирования без последствий средствами СПРК на УКПГ-2 развития масштабной общепромысловой катастрофы.

В виде графиков визуализированы выявленные закономерности ПТО, позволившие сформировать предвестники развития аварий и катастроф на ПТО ООО «ГДЯ», СНГП и ГПС «Орловка-2». Представлена информация о высокой экспериментальной воспроизводимости полученных результатов.
Отработана технология раннего обнаружения и парирования всех типов потенциально опасных самовозбуждающихся системных явлений на реальных ПТО инфраструктуры — автоколебаний. Представлены три случая их возбуждения на реальных газовых промыслах.
Результаты исследования. Показана фрагментарность и локальность систем аварийной защиты ПТО, базирующихся на принципе ALARP. Следствием этого стала его полная непригодность для раннего обнаружения и противодействия самоорганизованно возбуждающимся наиболее масштабным и затратным системным авариям — катастрофам, представляющим собой процессы многофакторные, ни один из факторов в которых не является определяющим. Предложенное авторами и доведенное до рабочего состояния альтернативное комплексное решение проблемы базируется на адаптированном к ПТО нефтегазового комплекса системном подходе.
Обработаны и проанализированы измеряемые параметры разных ПТО инфраструктуры — промыслов ООО «ГДЯ» и СНГП в моменты развития на них автоколебательных режимов, обусловленных самоподдерживающимися нелинейными механизмами взаимодействия элементов ПТО с постоянными (не колебательными) источниками восполнения энергии. Проиллюстрировано три таких режима самовозбуждения. Наиболее информативными при этом оказались переходные режимы работы оборудования.
По экспериментально отработанным авторами технологиям были проанализированы области критических режимов работы оборудования с выраженными потенциально опасными точками бифуркации. Представлен результат наложения обработок измеряемых параметров восьми натурных испытаний ПТО — графиков безразмерных амплитудно-частотных характеристик взаимосвязей реальной динамической системы: «вход — корпус охлаждения газа» → «выход — трубная обвязка корпуса» на частоте автоколебаний.
Обсуждение и заключение. Возможности ALARP не отвечают задачам системного мониторинга возникновения и развития опасных инцидентов на газовых месторождениях. Этот вывод можно отнести ко всем типоразмерам ПТО инфраструктуры России. Для обеспечения комплексной наблюдаемости, управляемости, безопасности и защищенности ПТО следует задействовать принципиально иные решения. Рекомендована комплексная научно-техническая программа: «Инновационные программно-аппаратные средства и технологии в обеспечение наблюдаемости, управляемости, безопасности ПТО инфраструктуры России».

***Ключевые слова*:** природно-техногенный объект, принцип ALARP, безопасность нефтегазовых промыслов, развитие системной аварии. противодействие развитию аварий

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Introduction. According to the Center for Research on the Epidemiology of Disasters (CRED), almost all large-scale system accidents are recorded post factum. This indicates a significant amount of work and efforts that are needed to ensure safety of natural and man-made facilities [1]. It should be emphasized that in this case, safety is a systemic (integral) nonlinear quality of a complex system. Scientific research in this area involves, in particular, the revision of stable stereotypes. One of them is the statement that the parts determine the properties of the entire object (including safety). It should be recognized that this theoretical approach (in some cases justified) does not find practical confirmation when it comes to the problems considered in the framework of this study. Not only the risks of epidemics and man-made disasters are growing in the world, but also the implementation of the worst scenarios and the enormous losses associated with them. The experience of recent years proves an extremely low awareness of the features of such processes and the inability to influence them.

The first full-fledged emergency protection systems in the world practice were created in Russia in the 50s and 60s of the last century. Their authors were specialists in rocket space engines. In the 1970s and 2010s, as part of the conversion, civil industries were able to use these unique achievements to solve safety problems of complex general technical infrastructure facilities. First of all, the developments were used at nuclear and thermal power facilities, in the oil and gas complex, and aviation. In the circumstances concerned in 1995, on the initiative of the NPO Energomash named after V.P. Glushko, the authors of the presented article formed an interdepartmental working group of the Russian Academy of Sciences. In 2014, it was legalized by the decision of the All-Russian Research Institute for Civil Defense and Emergency Situations of the Ministry of Emergency Situations of Russia (Federal Center for Science and High Technologies).

The group took part in the works listed below.

1. In 2006, for the first time in world practice, a system was created that was certified for explosion safety and allowed to counteract the development of a real large-scale industrial disaster.

2. In 2016, a Strategy for countering the development of disasters was developed and defended.

3. In 2017, on behalf of the President of the Russian Academy of Sciences, the strategy "Innovative technologies and means of protection against man-made accidents at industrial infrastructure facilities in Russia" was formed, scientifically and experimentally substantiated, and defended.

4. In 2021, a Comprehensive Scientific and Technical Project (CSTP) of the full innovation cycle "Innovative software and hardware and technologies to ensure the observability, controllability, and safety of the NTO infrastructure of Russia" was created, scientifically and experimentally substantiated, and defended.

We should emphasize that the formulation of the problem and the technologies focused on its solution were the result of work first on the Concept (on the instructions of the leadership of the All-Russian Research Institute for Civil Defense and Emergency Situations of the Ministry of Emergency Situations of Russia), and then on the Strategy of the Russian Federation to counter the development of Disasters (by the decision of the Presidium of the Russian Academy of Sciences).

From the point of view of safety, one of the essential non-linearities of complex multicomponent infrastructure objects is a violation of the superposition principle. The fact is that the safety of the NTO is not determined by the state and functioning of its constituent elements[1, 2, 3, 4].

Nevertheless, in the real conditions of NTO operation, the world practice remains, as it was 100 years ago, traditional, that is, locally oriented. It is based on the erroneous principle that the NTO is safe if all its elements are safe. This is due to the almost complete loss of control of man-made disasters, which on average are 4–5 orders of magnitude more costly in terms of consequences compared to local accidents in the NTO elements. Only in recent decades it has been possible to understand, scientifically and experimentally substantiate the physical mechanisms governing such incidents [1–4].

It should be noted that an application is ready for the development of a full innovation cycle CSTP "Creation of innovative software and hardware and technologies to ensure the observability, controllability and safety of natural and man-made infrastructure facilities in Russia". The project is focused on the creation of breakthrough domestic technologies to increase the competitiveness of the economy in compliance with the provisions of the basic documents of Russia's strategic development. The application has been approved for submission to the Council for Priority Areas of Scientific and Technological Development of the Russian Federation. As a result, within the framework of the all-Russian strategy, a unified system of natural and man-made security (USNMS) of the infrastructure of Russia will be created [1, 5, 6].

The aim of the work was to describe a new practice implemented in the conditions of a specific gas field and to justify the refusal to focus on solutions that take into account only the minimum practically acceptable risk, that is, built on the principle of ALARP (as low as reasonably practicable). Let us clarify that the promising, global goal of the authors' scientific and applied research, including those described in this article, was to create, within the framework of the Strategy of the Russian Federation, an object-oriented unified system of natural and man-made security (USNMS) of the infrastructure of Russia, an alternative output according to the ALARP ideology.

According to Rostekhnadzor of the Russian Federation, during the transportation of liquid and gaseous hydrocarbons, cases of local accidents at regularly operated enterprises numbered in the hundreds and thousands cases. In particular, there were:

– 545 cases of depressurization on the main pipelines during the last decade of the XX century;

– 42 thousand cases of depressurization on the infield pipelines during 2001 alone.

[1] Decree of the President of the Russian Federation of December 31, 2015 No. 683 "On the National Security Strategy of the Russian Federation". URL: https://www.consultant.ru/document/cons_doc_LAW_191669/ (accessed: 02.11.2023). (In Russ.).

[2] Decree of the President of the Russian Federation No. 642 of December 01, 2016 "On the Strategy of Scientific and Technological Development of the Russian Federation". URL: http://kremlin.ru/acts/bank/41449 (accessed: 02.11.2023). (In Russ.).

[3] Consolidated strategy for the development of the manufacturing industry of the Russian Federation until 2024 and for the period up to 2035. Approved by Decree of the Government of the Russian Federation No. 1512-r of June 6, 2020.URL: http://government.ru/docs/39844/ (accessed: 02.11.2023). (In Russ.).

[4] Idem.

Obviously, only large-scale and costly organized counteraction could solve the problem.

The world's first successful practice was implemented in Russia in the 50–60s of the XX century in the field of safety of heavy-duty liquid-propellant rocket engines for space purposes during development and routine fire tests [5]. It is known as the emergency protection system (EPS).

In the 80s, a similar emergency shutdown system (ESS) was created in the West for general technical facilities. It was based on the ALARP principle [6–9], which has been repeatedly refined in Russia and its numerous Russian versions[5] [8–10]. Let us note that the term ALARP originated in the 70s in the field of British legislation on health and safety at work, that is, outside the systematic approach. As a result, it retained many characteristic features of that time, but exhausted them.

At the same time, safety policy of oil and gas production and transportation according to the ALARP principle more often concerned the procedures for optimizing work processes. This practice was less often applied to the actual emergency protection due to the weaker scientific and experimental elaboration of issues related to the relevant processes.

Materials and Methods. The research focused on the problem of creating an EPS production chain of oil and gas production and transportation based on the ALARP principle [11–13]. It accompanied the project of creating the USNMS NTO, therefore, a comparative analysis of both approaches was carried out in the work.

As a rule, safety problems were solved by the interaction of:

– the customer (consumer of output products);

– the contractor (ideologist, developer and manufacturer of output products);

– the parties involved in the creation of NTO (design organizations and enterprises implementing projects).

In general, the object of research was an open dissipative dynamic system that combined elements that were interdependent and interacted with each other and with the external environment. Two complementary information components were taken into account to ensure safety of such NTOs:

– elements in the NTO (local accidents);

– NTO as a whole (a complex of interrelated elements, local accidents and systemic disasters).

A mandatory stage of such work was the coordination of the customer's request and the contractor's capabilities.

Each component was a set of processes with its own energy and indication.

Results. It should be emphasized that the study of the NTO elements in itself was not informative enough to understand its state as a whole [3–4]. The observability, controllability and safety of the NTO as a system were not determined by the characteristics of its constituent elements, even if all of them were taken into account.

Thus, according to ALARP, the most common cause of accidents and technological disasters was the human factor. This does not correspond to the modern point of view [3]. Nevertheless, the ALARP principle has become even more widespread in Russia than in the UK. In particular, it was recommended by GOST for risk management[6].

The current situation does not negate doubts about the validity of ALARP. Below are its statements that have caused explicit or implicit limitations for qualitative research on the NTO safety.

1. NTO elements do not interact with each other or their interaction can be neglected. This contradicts the real state of affairs. All NTO infrastructures, including oil and gas complexes, are multicomponent, complex dynamic systems. They are viable only with a controlled interaction of elements. That is, the fallacy of the statement is easily refuted by practice. Why is it not abandoned? The fact is that such an approach justifies simplifying the procedure for summing up the risks of the NTO elements in order to obtain an integral risk for the whole object.

2. The only material carriers and sources of danger to the NTO infrastructure are the elements that form them. The statement is true, but only in relation to local type accidents. The rule does not work if we are talking about system accidents — catastrophes that are more expensive than the local ones by an average of 4–5 orders of magnitude. Catastrophes are multifactorial phenomena. These are the consequences of violations of the normal dynamic interaction of the NTO elements with each other, NTO with its own control system, NTO with adjacent equipment, NTO with the external environment, etc.

3. The sources of danger in the NTO elements are statistically mutually independent. This assumption is wrong, first of all, in relation to the most severe system accidents — catastrophes that arise due to violations of the interaction of the NTO elements.

[5] GOST R IEC 61511-3-2011. Functional safety. Safety instrumented systems for the process industry sector. Part 3. Guidelines for the determination of the required safety integrity levels. URL: https://docs.cntd.ru/document/1200094220 (accessed: 02.11.2023). (In Russ.).

[6] GOST R 54505-2011. Functional safety. Risk management on railway transport. URL: https://docs.cntd.ru/document/1200094215 (accessed: 02.11.2023). (In Russ.).

4. The risk associated with the element has been taken as a measure of the element's danger. Other, more significant risks caused by violations of the interaction of elements with each other and with the external environment of the NTO are not taken into account. The measure of the NTO danger as a functional unit is determined by the sum of risks of its elements [6–11], [14]. It is unacceptable to summarize the risks associated with the NTO elements. And the point is not that they usually have different dimensions (with the help of the matrix apparatus of risks, the dimension can be excluded [14]), but in the statistical interdependence of the sources of the danger of NTO. According to the ALARP scenario, there is no way out of this situation.

As a result, it is necessary to operate with understated risk indicators compared to their actual values, which means underestimating the real dangers for NTO.

The above allows us to make a number of statements.

– ALARP suggests following an outdated local approach to solving safety problems of the NTO infrastructure, which limits the scope of its application. The situation is aggravated by the failure to mention the unsuitability of ALARP for solving problems of system analysis of the state and behavior of the NTO infrastructure.

– Specialists focused on working on ALARP do not have special tools for the study of the NTO infrastructure itself, the development of elements and in general EPS, as well as for the maintenance of the output result of ALARP, etc. Let us note that such tools are planned to be developed within the framework of the previously mentioned CSTP.

– ALARP specialists do not have a technology that can adequately provide the required informativeness, manageability and safety of the NTO.

– Equipping the NTO infrastructure with emergency protection systems based on ALARP does not meet the modern vision on the problem of ensuring the safety of NTO.

Thus, the main weakness of ALARP is the refusal to take into account the dynamic interaction of elements as part of the NTO infrastructure.

Experimental confirmations of the extreme importance of the dynamic interaction of the NTO elements of oil and gas fields. The authors of the presented article take the opposite position and have repeatedly received confirmation of its validity when conducting research and development work, including conversion, designed to ensure man-made safety of civilian facilities, taking into account the experience of space engine building. One of these civilian areas has become the extraction and transportation of oil and gas. It is important to note that the authors had unique specialized hardware and software resources and technologies (including of their own development).

Some results of full-scale tests of different standard sizes of NTO were obtained for the first time. To convey these results and the accumulated experience, the evidence-based data on the decisive role of the processes of interaction of the NTO elements are presented below. They are necessary for the formation of informative components of the NTO work processes, and can also be harbingers of large-scale, often spontaneously developing anomalies such as man-made disasters [1, 3]. In the real conditions of geographically distributed oil and gas fields, the interactions of elements were traced over distances:

– about 10 m at the facility safety levels;
– up to 100 m at the workshop levels;
– up to 10 km at the field level.

The authors did not conduct research at larger distances between the elements.

Let us list the constructs of the production links of oil and gas production and transportation, which form the dynamic interactions of the elements of the technical control system:

– energy producing units (combustion chambers, gas generators, cylinders of internal combustion engines, etc.);
– energy converters (pumps, compressors, turbine units);
– external and internal bindings of workshops interacting with other links, by-passes, input and output manifolds;
– energy storage links;
– wellheads.

Figures 3–7 in the article are the results of the analysis of the measured parameters of various NTOs infrastructure, which were investigated by the Interdepartmental Working Group of the Russian Academy of Sciences represented by the authors during field tests.

Let us start with the most common regular systemic phenomena in the oil and gas industry — self-oscillations caused by self-sustaining nonlinear mechanisms of the interaction of the NTO elements with constant (non-oscillatory) sources of energy replenishment. In the cases described below, the results from the authors' own experience of conducting field tests of oil and gas facilities were used, although the coverage was significantly wider and included thermal power plants, hydroelectric power stations, nuclear power plants, production and operation of heavy-duty diesel generators, turbo-expanding assemblies (TEA), etc.

The main attention was paid to the timely detected incidents, which, thanks to the use of technical means, did not develop into accidents and catastrophes. Thus, at the Yuzhno-Russian field of OJSC Severneftegazprom, when fixing a powerful self-oscillating process of the dynamic interaction of the pair "ground structure of the well cluster → adjacent subsurface", an emergency shutdown of the existing well cluster was triggered (Fig. 1).

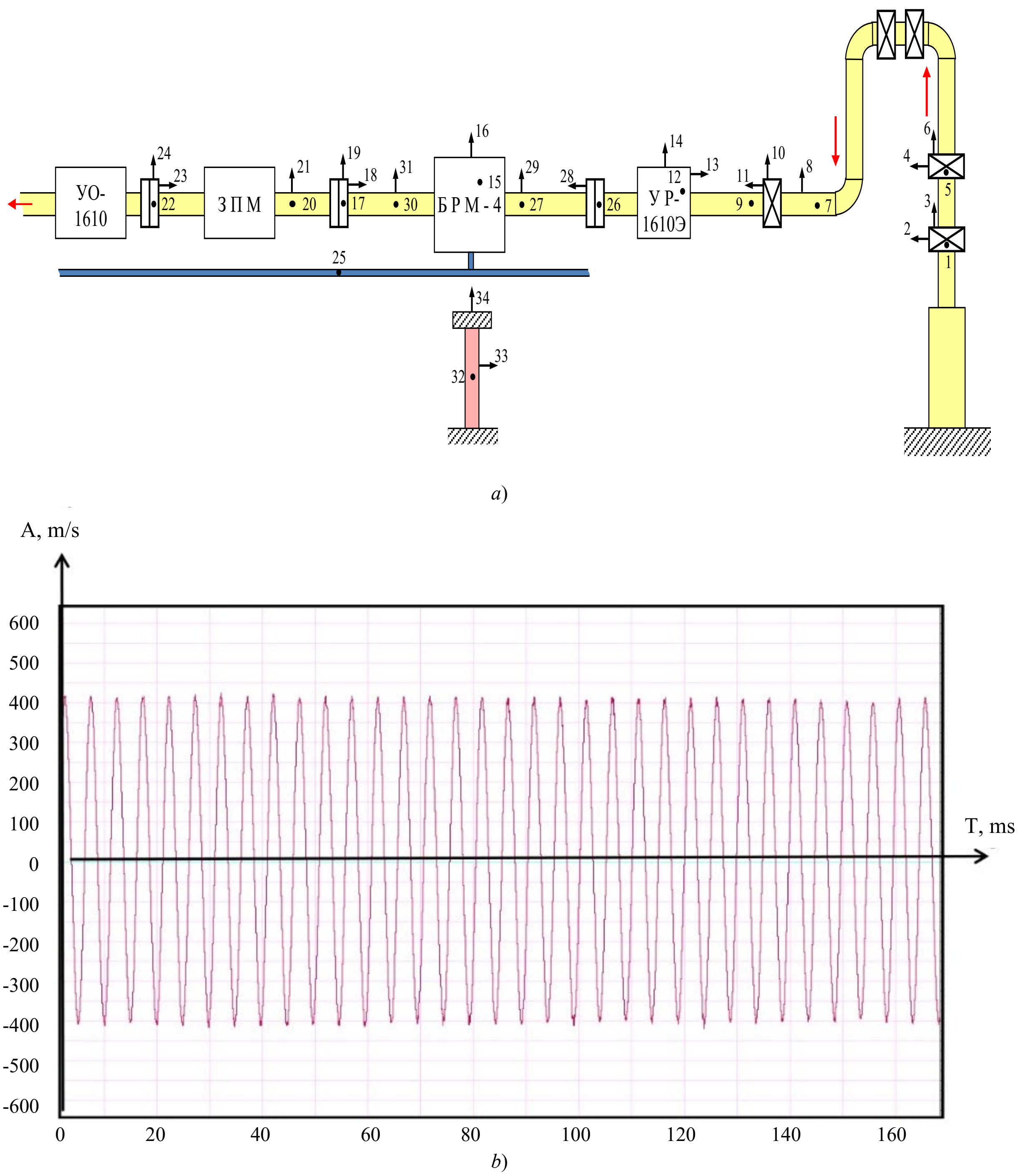

Fig. 1. Self-oscillating process of the dynamic interaction of the pair "ground structure of the well cluster → adjacent subsurface ", recorded at the Yuzhno-Russian field of OJSC Severneftegazprom: *a* — wellhead; *b* — fragment of the vibration parameter of the pipe head of the wellhead at the initial moment of self-excitation of powerful natural and man-made self-oscillations with a frequency of ≈ 200 Hz

Let us explain that part a) presents the design of the wellhead with a 34-channel system for measuring and recording vibration parameters of the 2nd string of the 9th well cluster. The black arrows show the locations of the sensors and the measurement directions of the vibration parameters of the structure of the 2nd string of the 9th well cluster, the red arrows show the direction of movement of the gas flow. Here, УО is a shut-off device, ИБ is a measuring unit, БРМ is a methanol control unit, and УР is a regulating device.

The authors of the article had to urgently distract themselves from their main work and take part in clarifying the nature of the dangerous phenomenon. As the subsequent calculation and analysis of metal from critical sections showed, the fatigue strength of the metal structure was exhausted in the next 2–2.5 hours.

Additional processing of the measurement results made it possible to establish dislocations of:

– a constant source of energy replenishment (adjacent bowels of the cluster of wells);

– a nonlinear oscillatory circuit (cluster of wells).

The authors have worked out the appropriate methodology, software and hardware in relation to space propulsion. At the frequency of excitation of self-oscillations of all pairs of measured vibration parameters of the wellhead, coherence almost coincided with unity.

Figures 2 and 3 present the location and characteristics of the case of self-excitation of self-oscillations. The authors recorded it when they conducted full-scale tests of the integrated gas treatment plant (IGTP) at Gazprom Dobycha Yamburg LLC (GDYA) in the frequency range of 36-56 Hz (depended on the operating mode).

The physical mechanism was identified as self-oscillation — a strong dynamic interaction of the gas drying housing equipment and its external strapping. The most informative tests turned out to be on transient modes of operation of the equipment:

– slow throttling from 100% of the mode to 65% (in time from 550 seconds to 750 seconds);

– slow subsequent forcing from 65% of the mode to 85% (in time from 1200 seconds to 1300 seconds).

Fig. 2. At the integrated gas treatment plant (IGTP-2), a strong nonlinear interaction of dynamic links occurred "gas drying body (on the right, in the background) → external binding"

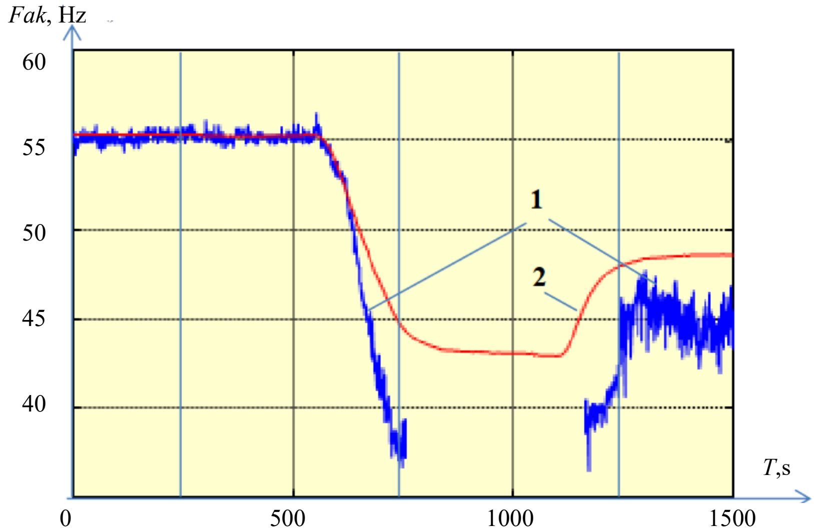

Fig. 3. IGTP-2. Time dependence of the frequency of self-oscillatory interaction of dynamic links "gas drying body → its external binding": 1 — according to the processing of the results of field tests; 2 — according to the accompanying theoretical calculation

The acceptance tests of the explosion-proof prototype of the disaster response system (DRS) at the GDYA IGTP-2 in 2006 turned out to be unique in terms of information content and practical physical interpretation of the discovered phenomenon. To confirm the experimental reproducibility of the results, 10 similar full-scale tests of IGTP were planned in the modes of regular forcing and throttling. The only non-rigid exception, as expected, was the 8th test. Let us note that complex systems had different time scales. In the 8th case, in order to obtain a higher time resolution than in the previous seven tests, the process gradient was reduced by more than half.

Due to the exceptional importance of the test results, in addition to regular measurements, the program regulated the deployment of a 96-channel geographically distributed system for measuring various parameters of the facility. At the automated workplace of the DRS operator in the gas drying building, the parameters were presented after group synchronization and centralization (GPS satellite system was used).

Pronounced bifurcation points in the working processes of the production field (at ≈ 18% of the nominal value) attracted the attention of the authors long before the acceptance tests. However, this phenomenon had not previously caused incidents, so the tests were not canceled. Figure 4 shows the result of graphs overlay of eight of the planned ten DRS tests.

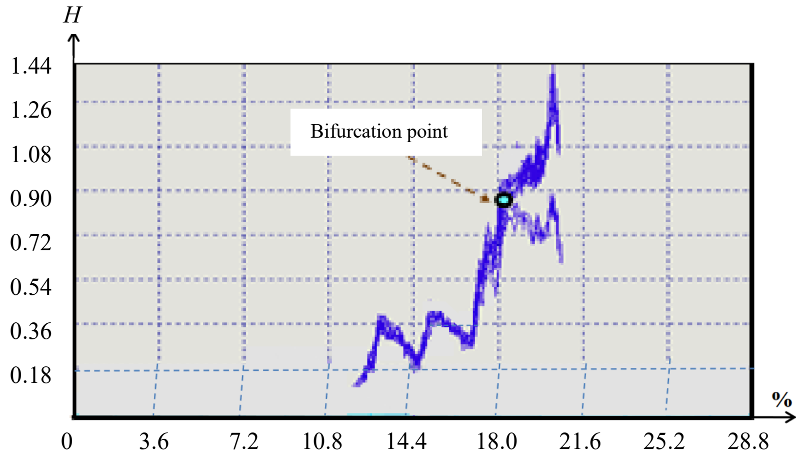

Fig. 4. IGTP-2. The result of eight full-scale tests overlay— graphs of dimensionless amplitude-frequency characteristics and relationships of the dynamic system: "inlet — gas cooling housing" → "outlet — pipe casing" at the frequency of self-oscillations

Here, in the forcing sections, after passing the bifurcation points, the lower branch of the curve was used in tests 1, 3, 4, 6, and the upper branch was used in tests 2, 5, 7, 8.

It is clear that the blurriness of the graph in Figure 4 (as well as the graphs in Figures 6, 7 and 8 for other objects) is explained not by errors in measuring the NTO parameters, but by overlays of the results of processing data from field tests conducted at the same values of the operating parameters of each object. At the same time, the blurriness of the graphs is important from the point of view of informativeness. It makes it possible to:

– clearly present the degree of reproducibility of test results (or other parameters, depending on the formulation of the problem), that is, to draw conclusions about the correctness or incorrectness of the problem being solved;

– take reasonable tolerances for the tasks of making decisions about technical and (or) functional state of the NTO in the forms of dependence on the operating parameters of the NTO in the entire range or sub-ranges of values.

Figure 5 shows a fragment of the processing of the results of the eighth test in the vicinity of the critical point (18% of the nominal value) at the throttling site with the spontaneous development of a systemic technogenic accident. At that time, there was no gas automation in the cooling and drying housing, so the situation was adjusted manually using a bypass. They did not use a conventional emergency stop, but reverse forcing.

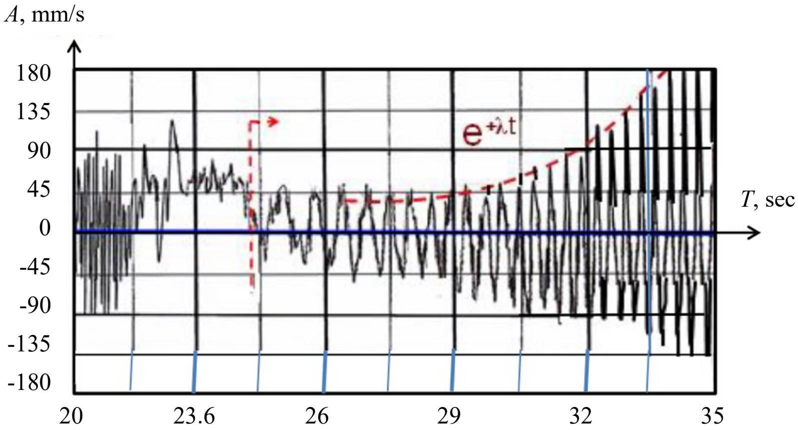

Fig. 5. IGTP-2. The initial stage of spontaneous development of a systemic disaster

Experimentally determined post factum, the horizon of the disaster forecast turned out to be unprecedentedly large — $\tau^* = 90$ sec at the values of Lyapunov exponents in the areas of excitation and damping of oscillations, respectively: $\lambda_1 = +\,0.14$ Hz and $\lambda_2 = -0.38$ Hz. We have established the reason for such a rare phenomenon in the NTO operation. It is due to the discovered (apparently for the first time in world practice) mechanism of a two-stage scenario of excitation and development of a catastrophe. At the first step of the previously established critical mode with the bifurcation point shown in Figure 4, there was a shop system excitation of a group of production field elements — turbo expander units in interaction with an external pipe binding. It also played the role of a trigger mechanism in the second step, which was characterized by a strong interaction of the wellheads with the subsurface.

Subsequently, the development of this general industrial disaster was qualified as the first in the world practice to detect in time (which made it possible to take countermeasures) an extremely dangerous regional man-made natural earthquake with a magnitude of 6 to 7 points on the Richter scale. The energy source was the subsoil, the constructs of the clusters of wells worked as a trigger mechanism. A decisive role was played by manually lowering the throttling gradient at the eighth acceptance test and, accordingly, increasing the production field time in the danger zone — in the vicinity of the critical bifurcation point at ≈ 18% of the nominal value.

Now it has become a universal practice to detach resonant frequencies from dislocation zones or to accelerate their overcoming in transient modes. Examples include space rocket engines, nuclear power plants, hydroelectric power plants, aviation equipment, etc.

Two factors realized during the acceptance tests are of exceptional importance.

1. A systematic approach to the organization and conduct of DRS tests. Formation of a package of initial experimental data to understand the essence of the mechanism and counteract the development of an extremely dangerous phenomenon — a general industrial disaster, which geographically and in time coincided with a man-made natural earthquake. The local approach peculiar to ALARP and its output products was not in demand in this case.

2. High information content. The standard system for measuring production field parameters has been supplemented. A geographically distributed parameter measurement system with group synchronization and centralization of parameters was used. The regularly measured production field parameters indicated the development of an emergency:

– a fraction of a second before its completion, when emergency protection was impossible;

– only by secondary signs in the high-frequency range (the main events were recorded at low frequencies).

Figure 6 shows overlays of the results of processing of twelve full-scale tests of turbo-expanding units in the gas drying housing of IGTP-2 LLC GDYA during one and a half months of repair.

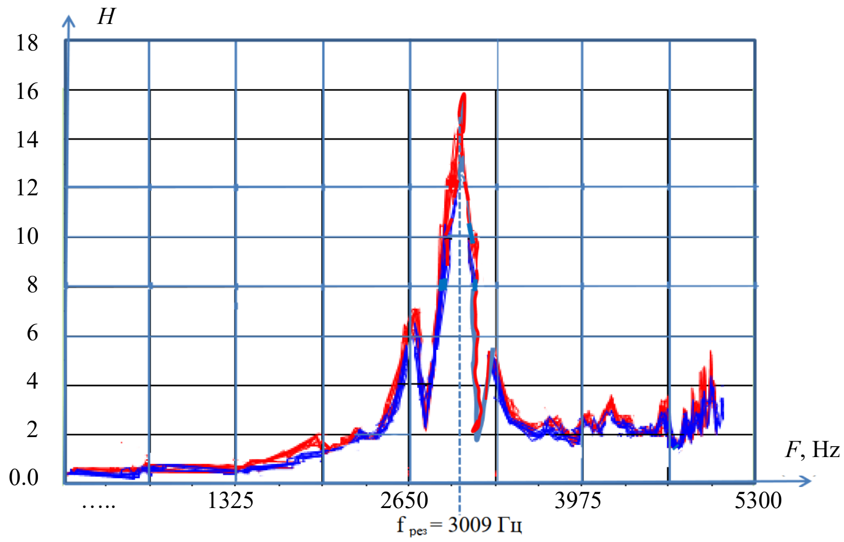

Fig. 6. Experimentally reproducible amplitude-frequency characteristics of the dynamic system "TEA-2 → TEA-7"

In this case, the authors used a two-channel modular unit for high-precision synchronous isolation of frequency components $53F_p$ (53 — the number of turbine blades of the studied standard size of turbo-expanding assemblies) in the axial vibration parameters of TEA-2 and TEA-7 turbines. The modes of slow forcing (red curves) and throttling (blue curves) of TEA-2 operated. The work was carried out in the nominal normal mode of TEA-7.

Thus, the amplitude-frequency characteristics of the resonant type (Fрез = 3009 Hz) of the potentially dangerous high-quality ($Q \approx 76.5$) dynamic interaction of TEA-2 and TEA-7, reproduced in a wide frequency range up to 5300 Hz, were evident. It was necessary to develop and implement serious counteraction measures. In addition, additional field tests were conducted to confirm their effectiveness. This was a unique case of experimentally reproducible system testing of TEA-2 in the modes of starts and stops of its dynamic interaction with an adjacent, operating at the nominal mode TEA-7 in a wide frequency range. This experimentally proven approach and the technology adequate to it can be used in the operation of any rotary and (or) piston type equipment. It is important to keep in mind that formed according to similar characteristics (see Fig. 6) harbingers of development of emergency situations at NTOs are systemic. They are suitable for solving problems of identifying the type of developing accident — local and systemic (disaster).

Figures 7 and 8 present experimentally reproducible systemic patterns of interaction between gas pumping units (GPU). They were worked out at the Orlovka-2 gas pumping station (Ukraine) and are not fundamentally monitored by ALARP-based systems. The total number of field tests according to Fig. 7 (GPU-1 → GPU-2) is 14, according to Fig. 8 ("GPU—4 → GPU-5") is 18.

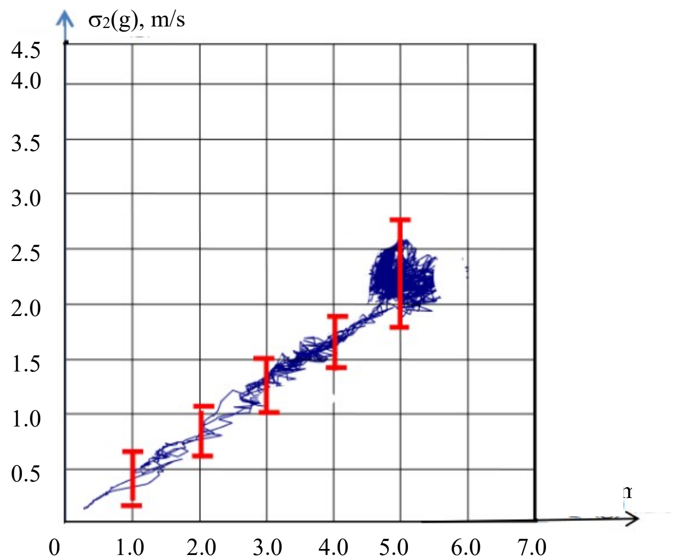

Fig. 7. GPS "Orlovka-2" (Ukraine). Reproducible patterns of interaction "GPU-1 → GPU-2"

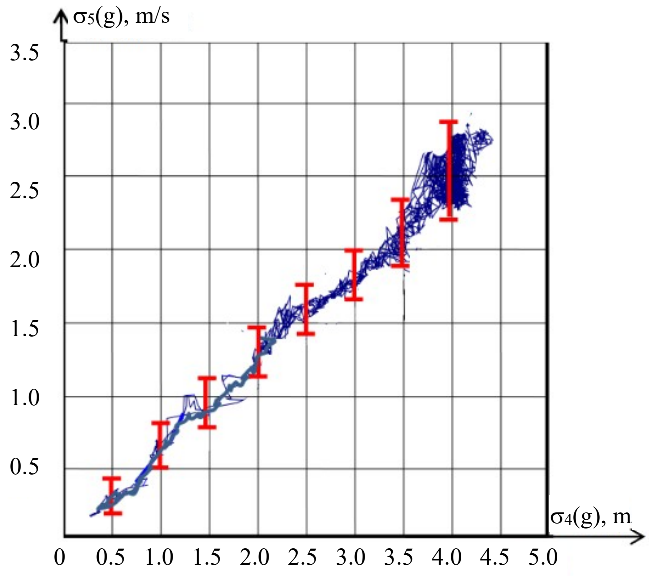

Fig. 8. GPS "Orlovka-2" (Ukraine). Reproducible patterns of system interaction "GPU-4 → GPU-7"

In the figures, the patterns are shown in the form of hodographs in the form of dependencies, measured in the horizontal and vertical directions of the mean square root values of the vibration velocities of the GPU on the total gas flow through the GPS — *g*. For certainty, the frequency range of measurements of mean square root values of 0.1–5 Hz was chosen. According to statistics, it is in this range that processes with a large self-organized concentration of energy often occur in NTO structures, which provoke the development of emergency outcomes — both local and more costly systemic ones. Despite the significant differences in the physical mechanisms, in this case, the results obtained can be used in the operation of rotary-type equipment, and with appropriate adaptation in the operation of non-rotary equipment.

For the development of the above-mentioned prototype of the DRS and the Strategy of the Russian Federation for countering the development of systemic accidents [1, 3], are essential:

– reproducibility of the results of field tests;

– experimental validity of statistically correct applied results.

Let us also note the importance of the typical scenario expected by specialists for the development of systemic accidents of different physical nature. It took at least ten years of targeted scientific and experimental work to confirm the reproducibility of the results. This made it possible to implement in the DRS and then reflect in the Strategy of the Russian Federation a set of unified algorithms and technical means for early detection, monitoring and protection against all types of man-made accidents.

An extremely important quality of this complex has been worked out — object orientability (the possibility of deep adaptation to almost any standard sizes of the NTO infrastructure).

We also note a characteristic feature of the system approach, which allows us to draw the right conclusions even if the experimental reproducibility of the results of the NTO full-scale tests is weak or not detected at all. It should be borne in mind that the same element of a complex system (for example, a compressor) demonstrates different properties and behavior, even if it functions as part of a single NTO. It depends on whether the situation is considered before or after the repair. This effect is easily confused with poor reproducibility of compressor test results.

Comparative analysis results of emergency protection systems adequate to the ALARP principle and the CSTP system approach. In almost all publications related to the ALARP principle, there are conditions from which ALARP proceeds. For some reason, they have to be executed by themselves, and this is a reason for criticism. The ALARP principle can be unconditionally used for a class of objects that are collections of such objects that are not related to each other, do not interact and are statistically independent. Thus, the usefulness of ALARP is limited to individual studies outside the system of each element of the NTO. Also, outside the system, the class of local accidents inherent in the elements is considered. The ALARP principle is not suitable for an adequate study of NTO as a whole structure, the formation of adequate symptoms, decision-making algorithms, etc. Using any tools based on the ALARP ideology (and EPS as well), we must understand that we are going to a conscious restriction.

The only way out seems to be the rapid creation of safety systems that are alternative to those that focus on ALARP. The foundation for new solutions should be the foundation formed for the implementation of a comprehensive scientific and technical program "Creation of innovative software and hardware and technologies to ensure the observability, manageability and safety of natural and man-made infrastructure facilities in Russia".

Here are the main arguments for the readiness to create safety and emergency protection systems within the framework of the CSTP as an alternative to the EPS according to the ideology of ALARP.

– Certified prototypes of professional tools have been created, including in explosion-proof design, for experimental testing of components of the system for countering the development of accidents and catastrophes.

– Emergency protection systems according to the CSTP are based on combined local and systemic approaches to the study of the NTO infrastructure within the framework of the theory of self-organized criticality [3].

– The emergency protection systems according to the CSTP take into account the discovery of the 50–60s of the Russian space engine industry [6]. We are talking about two types of the physical nature of accidents. In modern terminology, they are called local (in the NTO elements) and large-scale, systemic (in NTO as an integral functional unit). According to the ALARP scheme, the EPS reacts to the development of only low-cost local accidents.

– Emergency protection systems according to the CSTP are ready to make motivated decisions about the beginning of the development of all types of local accidents and systemic accidents in the NTO. This distinguishes them from EPS according to the ALARP scheme, which reacts only to local accidents.

– In the emergency protection systems according to the CSTP, the readiness to transfer the NTO to a safe state has been achieved in two scenarios. The first one is the transfer of the NTO to gentle modes of operation. Second: emergency shutdown in response to motivated decisions about the development of emergency critical situations.

– Restrictions on the scope of application of emergency protection systems according to the CSTP according to the type of a priori conditions for EPS according to the ALARP scheme have been lifted.

– In emergency protection systems according to the CSTP, the symptoms of the development of local, systemic critical conditions of NTO and the rules for making decisions on the transfer of NTO to a safe state have been scientifically and experimentally worked out.

– Readiness has been achieved (when making an appropriate decision) to work out a high-speed mechanism for transferring the NTO to a safe state for the most dangerous explosive-type accidents with a characteristic development time $\Delta t \approx 30–70$ ms.

Discussion and Conclusion. The emergency protection systems developed according to the CSTP "Observability, manageability, safety of the NTO infrastructure of Russia" are considered. Their capabilities are evaluated in the conditions of the Northwestern region of the Russian Federation [1]. The new approach is compared with the ALARP principle, which is widespread in the West and in Russia.

It is shown that ALARP has outlived its usefulness, since its local orientation does not meet the tasks of system monitoring of the IT infrastructure [8–14]. The ALARP approach remained at the level adopted at least 100 years ago, in the first half of the twentieth century. This is how it is necessary to evaluate developments implemented under the ALARP scheme and their output products, including emergency protection systems [8–14].

Research and practice indicate that the ALARP methodology does not provide comprehensive observability, manageability, and safety of natural and man-made infrastructure facilities. For this reason, the ALARP-based approach does not provide timely, high-quality indication of the development of devastating system crashes — catastrophes.

Emergency protection systems created according to the proposed CSTP project integrate local and integrated approaches to infrastructure monitoring within the framework of the theory of self-organized criticality [3].

The prospects of replacing ALARP-based approaches with solutions corresponding to the CSTP are shown.

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Claimed contributorship:

FM Deduchenko: formulation of the basic concept, goals and objectives of the study, calculations, preparation of the text, formulation of the conclusions;

AN Dmitrievsky: academic advising, analysis of the research results, revision of the text, correction of the conclusions.

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А.Н. Дмитриевский — научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

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Development of Mechanisms for Industrial Safety Culture Improvement Based on Employee Survey Analysis Results

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Abstract
Introduction. Ensuring industrial safety (IS) is one of the priority goals of any company. It is obvious that achieving its high level is impossible without the formation of a safety culture among employees, since their wrong actions can lead to emergencies and death of people at hazardous production facilities. The concept of industrial safety culture (ISC) is interpreted in different ways, but all definitions are united by the need for employees to realize that industrial safety should become their main goal and internal need. To date, there are many methods for determining the degree of ISC development. They are actively and successfully used at many enterprises. At the same time, it should be noted that the Russian legislation lacks, in particular, a methodology for quantifying the industrial safety culture specifically at the enterprises of the oil and gas complex, which have their own characteristics and specifics. Therefore, the introduction of a new quantitative approach to assessing the effectiveness of management of industrial safety culture has important scientific and practical significance on the industry agenda. The aim of this work in this regard was to develop mechanisms to increase the ISC level at one of the gas transportation enterprises of the country based on the results of the survey of its employees.
Materials and Methods. For the analysis, the results of a three-level questionnaire conducted in 2021 and 2022 were used, which included socio-biographical characteristics of employees, their assessments on specially developed 16 components of industrial safety, as well as the interview of focus groups on six selected IS components.
Results. During the analysis of the questionnaires, an increase in the level of industrial safety culture was established from the predicted (third level) to the proactive (fourth level) according to the five-level classification of the International Association of Oil and Gas Producers (IOGP).
Discussion and Conclusions. The comparative analysis demonstrated positive dynamics of the results of the ISC level assessment by the employees of the gas transport enterprise. Its increase at this enterprise was achieved through the introduction and implementation of proactive measures, such as the development of personal obligations of employees in the field of safety, their maximum involvement in the development of competencies in the field of industrial safety, ensuring openness/transparency of communications on safety issues, and the formation of a positive attitude of employees to changes in this area.

Keywords: industrial safety culture, maturation level, focus groups, survey

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Научная статья

Разработка механизмов повышения культуры производственной безопасности по результатам анализа анкетирования работников

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Аннотация
Введение. Обеспечение производственной безопасности (ПБ) является одной из приоритетных целей любой компании. Очевидно, что достижение ее высокого уровня невозможно без формирования культуры безопасности у работников, так как их неправильные действия могут повлечь создание аварийных ситуаций и гибель людей на опасных производственных объектах. Понятие культуры производственной безопасности (КПБ) трактуется по-разному, однако все определения объединяет необходимость осознания работниками того факта, что производственная безопасность должна стать их главной целью и внутренней потребностью. На сегодняшний день существует немало методик для определения степени развития КПБ. Они активно и успешно применяются на многих предприятиях. Вместе с тем следует отметить, что в российском законодательстве отсутствует, в частности, методика количественной оценки культуры производственной безопасности конкретно на предприятиях нефтегазового комплекса, имеющих свои особенности и специфику. Поэтому внедрение нового количественного подхода к оценке эффективности управления культурой производственной безопасности имеет важное научное и практическое значение в отраслевой повестке дня. Целью данной работы в связи с этим является разработка механизмов для повышения уровня КПБ на одном из газотранспортных предприятий страны, предпринятая по результатам анализа анкетирования его работников.
Материалы и методы. Для анализа использовались результаты трехуровневого анкетирования, проведенного в 2021 и в 2022 годах, которое включало в себя социально-биографические характеристики работников, их оценки по специально разработанным 16 компонентам производственной безопасности, а также интервьюирование фокус-групп на предмет шести выделенных компонентов ПБ.
Результаты исследования. В ходе проведенного анализа анкет было установлено повышение уровня культуры производственной безопасности с прогнозируемого (третьего уровня) до проактивного (четвертого уровня) согласно пятиуровневой классификации Международной ассоциации производителей нефти и газа (IOGP).
Обсуждение и заключение. Сравнительный анализ продемонстрировал положительную динамику результатов оценки уровня КПБ работниками газотранспортного предприятия. Повышение его на данном предприятии достигнуто благодаря внедрению и реализации проактивных мероприятий, таких как разработка личных обязательств работников в области безопасности, их максимальная вовлеченность в процесс развития компетенций в области производственной безопасности, обеспечение открытости/прозрачности коммуникаций по вопросам безопасности, формирование позитивного отношения работников к изменениям в этой сфере.

Ключевые слова: культура производственной безопасности, уровень зрелости, фокус-группы, анкетирование

Благодарности. Авторы выражают признательность сотрудникам газотранспортного предприятия за проявленный интерес к обсуждаемой теме и добросовестное прохождение анкетирования и интервьюирования, благодарят редакционную коллегию журнала и рецензента за профессиональный анализ и рекомендации для корректировки статьи.

Для цитирования. Суфиянова М.А., Волохина А.Т., Глебова Е.В. Разработка механизмов повышения культуры производственной безопасности по результатам анализа анкетирования работников. *Безопасность техногенных и природных систем*. 2023;7(4):70–79. https://doi.org/10.23947/2541-9129-2023-7-4-70-79

Introduction. Currently, the development of industrial safety at oil and gas complex enterprises is based on a risk-oriented approach, which means the integration of risk analysis and management methodology with the existing management systems. As practice shows, the implementation of this approach leads to the formation of a high industrial safety culture in companies.

Within the framework of new standard GOST R ISO 45001-2020 "Occupational health and safety management systems. Requirements with guidance for use"[1] the efficiency evaluation of the company's economic activity is inextricably linked with the evaluation of its achievements in the field of industrial safety.

The requirements for leadership and commitment of top management to achieve the goals set, as well as the involvement of employees in the identification of hazards and risks, the development and management of a management system are among the significant innovations of this standard. Indeed, competent formation and implementation of leadership in production is an extremely difficult task for the vast majority of companies. Only a few enterprises manage to form a high industrial safety culture through the introduction of leadership practices.

The industrial safety culture today is one of the most important elements of the occupational safety management system in all companies [1–3]. There are a sufficient number of methodological approaches to determining the degree of development of the ISC [4, 5]. Well-known models that are often found in the practice of international companies are the Bradley curve, the M. Fleming model and the P. Hudson model [6, 7]. These models were developed based on the experience of the world's leading companies and represent the stages of development of the occupational safety management system, which allows you, after conducting a specific analysis, to identify areas of safety culture that need to be improved [8–10]. For example, DuPont has more than two million questionnaires in its database covering a wide range of industries in 45 countries and more than 10,000 objects that can be visualized and compared with other industry companies to evaluate key indicators of their safety culture [11–13].

Materials and Methods. Based on the analysis of these international practices, an original methodology for assessing the industrial safety culture was developed using a three-stage questionnaire (three questionnaires) with subsequent processing of the results according to the specified criteria.

Questionnaire No. 1 contained 10 questions, including an assessment of socio-biographical characteristics of employees. It was assumed that they had a certain effect on the awareness of the importance of ensuring safety, on understanding and fulfilling the requirements of production instructions. Another part of the questions was aimed at determining the attitude of employees to the idea of zero injuries, readiness to take responsibility for their actions in relation to safety at work.

Questionnaire No. 2 offered questions for evaluating 16 individual components of ISC presented in Figure 1.

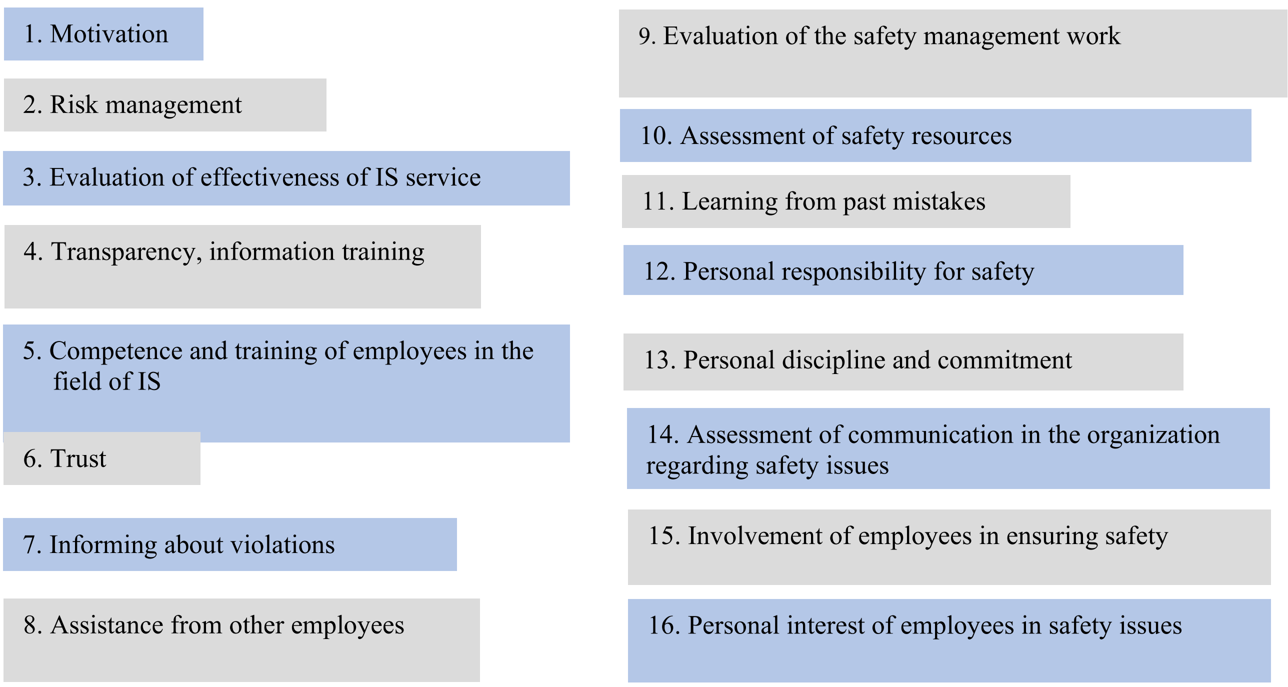


Fig. 1. ISC components

[1]GOST R ISO 45001-2020. *Occupational health and safety management systems. Requirements with guidance for use.* Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200175068 (accessed 30.08.2023). (In Russ.).

Four statements were made for each of the components, two of which were positive and two were negative. The employees had to choose the degree of agreement or disagreement with the proposed statements. For further data processing, all answers were transferred to a 5-point scale.

For the interviewing stage of the focus group, an original authors' questionnaire No. 3 was developed, which made it possible to assess such ISC components as motivation, competence and training of employees in the field of occupational safety and health, assessment of communications in security issues, policy and shared values, assessment of resources for security, and learning from past mistakes.

Interviewing about the state and level of ISC development was with the employees of seven professional categories: managers (administration), specialists (administration), line managers (production units of the main activity), line managers (production units of secondary activity), specialists (production units of the main activity), specialists (production units of secondary activity), and workers. The interviewing format was face-to-face (directly by an on-site auditor) and online (by filling out by employees a specially designed electronic Yandex.Form). All the answers received as a result of face-to-face interviewing were later entered into Yandex.Forms. The estimated time to complete the interview/questionnaire was 30 minutes.

As a result of filling out the Yandex.Form, all the answers were converted into points with the subsequent finding of an assessment by employees of both a separate ISC component (the average score for four statements for this component), and in general all 16 components (the average score for 16 components found) on a scale from 1 to 5.

The conversion of the average ISC assessment values by the employees to the five-level classification of the International Association of Oil and Gas Producers (IOGP) was carried out according to the scale shown in Figure 2, where:

– Level 1 — initial. The ISC concept was virtually absent, all safety measures were random, the requirements were not met;

– Level 2 — reactive. The ISC level was not developed, but certain safety measures were taken every time after the realization of an adverse event;

– Level 3 — predictable. The ISC level began to rise and gradually tended upward due to the creation and implementation of formalized approaches to industrial safety management;

– Level 4 — proactive. The ISC level was quite high, the values and leadership confirmed by the results ensured continuous improvement of industrial safety;

– Level 5 — creative. The industrial safety system was a way of doing business[2].

Results. Figure 3 provides the results of the survey of employees conducted in 2021 and in 2022 in the form of a comparative histogram. These histograms demonstrate the positive dynamics of the ISC assessment results by the employees of the enterprise.

The ISC components that received the highest ratings in both 2021 and 2022 were "Assessment of the effectiveness of IS service" (2021 — 3.86, 2022 — 4.33), "Personal responsibility for safety" (2021 — 3.86, 2022 — 4.31), "Assessment of the work of management to ensure safety" (2021 — 3.79, 2022 — 4.26). These assessments related to the proactive level of ISC and meant that there were no cases of concealment of incidents at the enterprise, employees had the opportunity to contact the management with questions about safety, they were aware of their personal responsibility for it and highly appreciated the work of the IS service. At the same time, it was worth paying attention to the minimum estimates: "Motivation" (2021 — 3.41, 2022 — 4.15), "Assessment of resources for safety" (2021 — 3.43, 2022 — 4.18). The minimum estimates of 2021 referred to the projected ISC level, while the minimum estimates of 2022 referred to the proactive one, and this was despite the fact that the components showed the lowest number of points in 2022. These data indicated a lot of work done with an emphasis on these components.

[2]*IOGP Report 453 – Safety Leadership in Practice: A Guide for Managers* International Association of Oil & Gas Producers Bookstore (IOGP). URL: https://www.hpog.org/resource-centre/iogp-papers/new-download/ (accessed 30.08.2023)

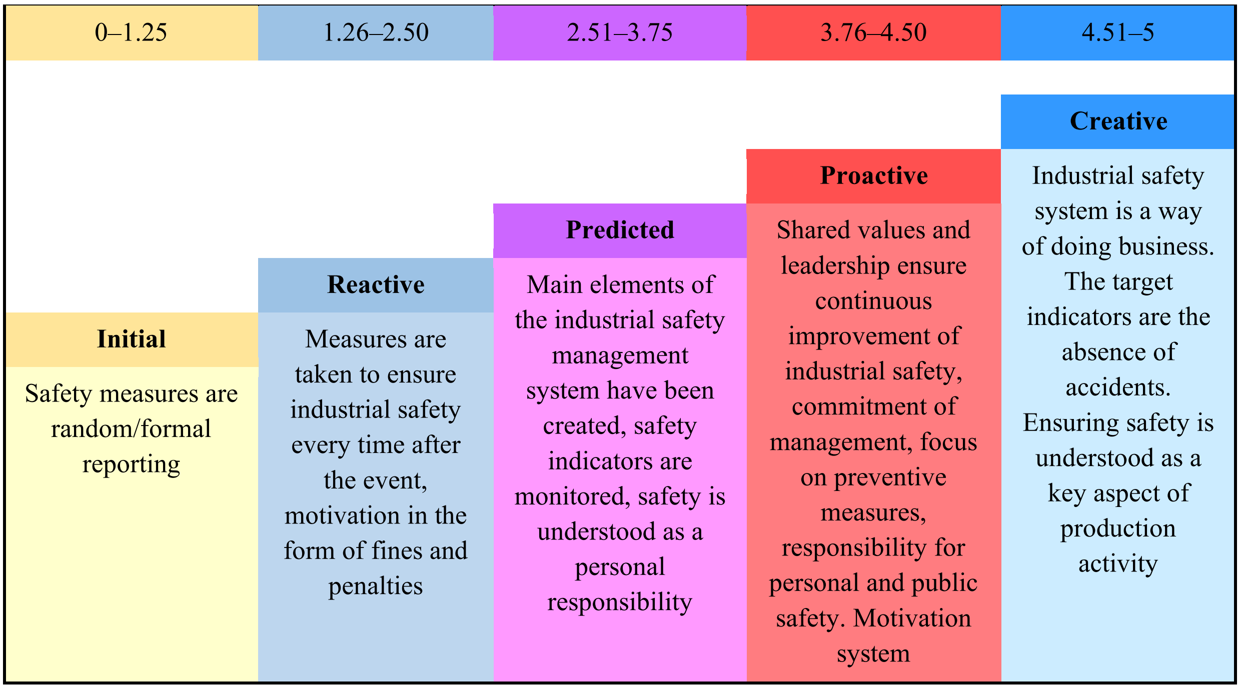


Fig. 2. Results of the survey on the international five-level classification of oil and gas producers (IOGP) [13]

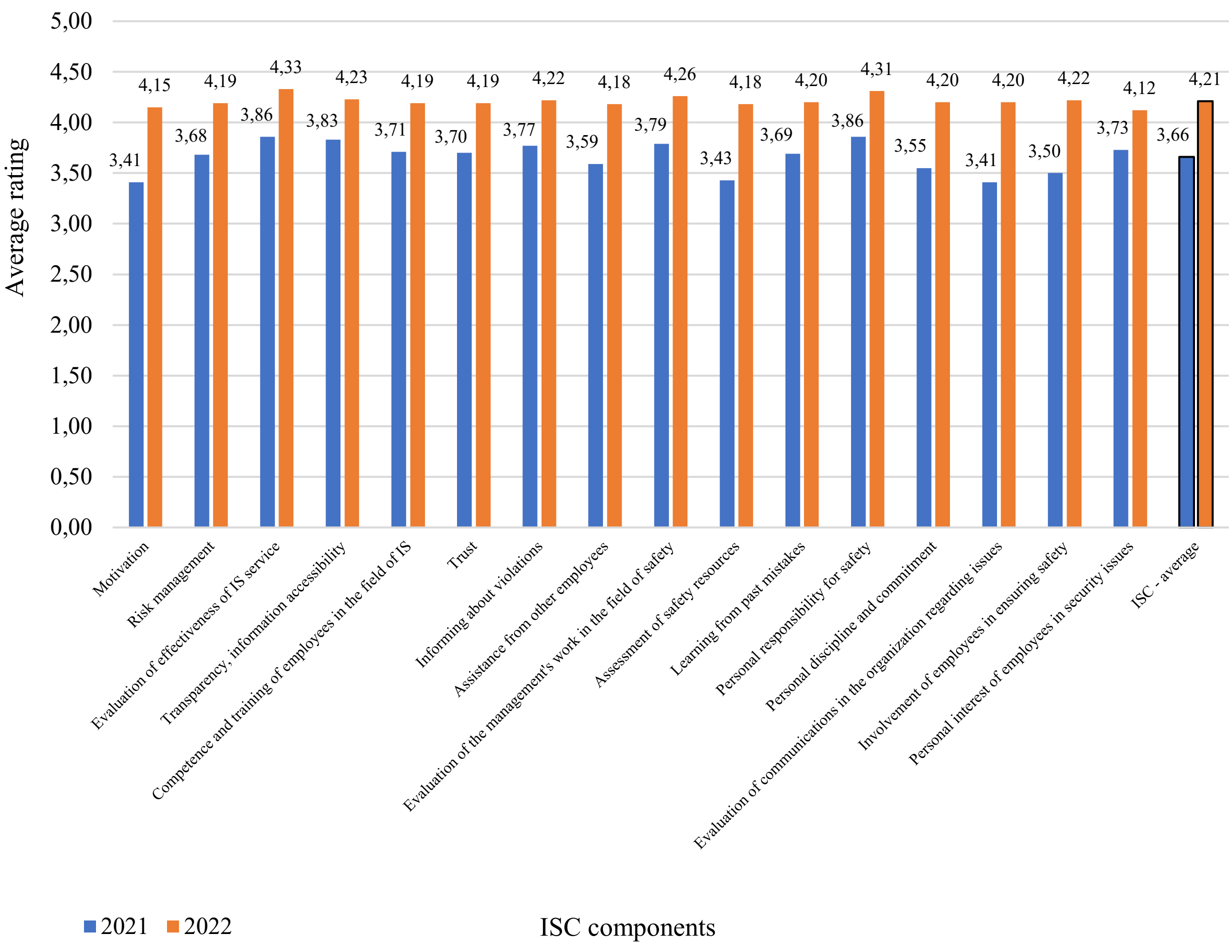


Fig. 3. ISC level assessment by gas transportation company employees in 2021 and 2022

The average ratings of all components of the industrial safety culture for each professional category and the average ISC value for the enterprise as a whole were also calculated. Figure 4 provides the comparative histogram.

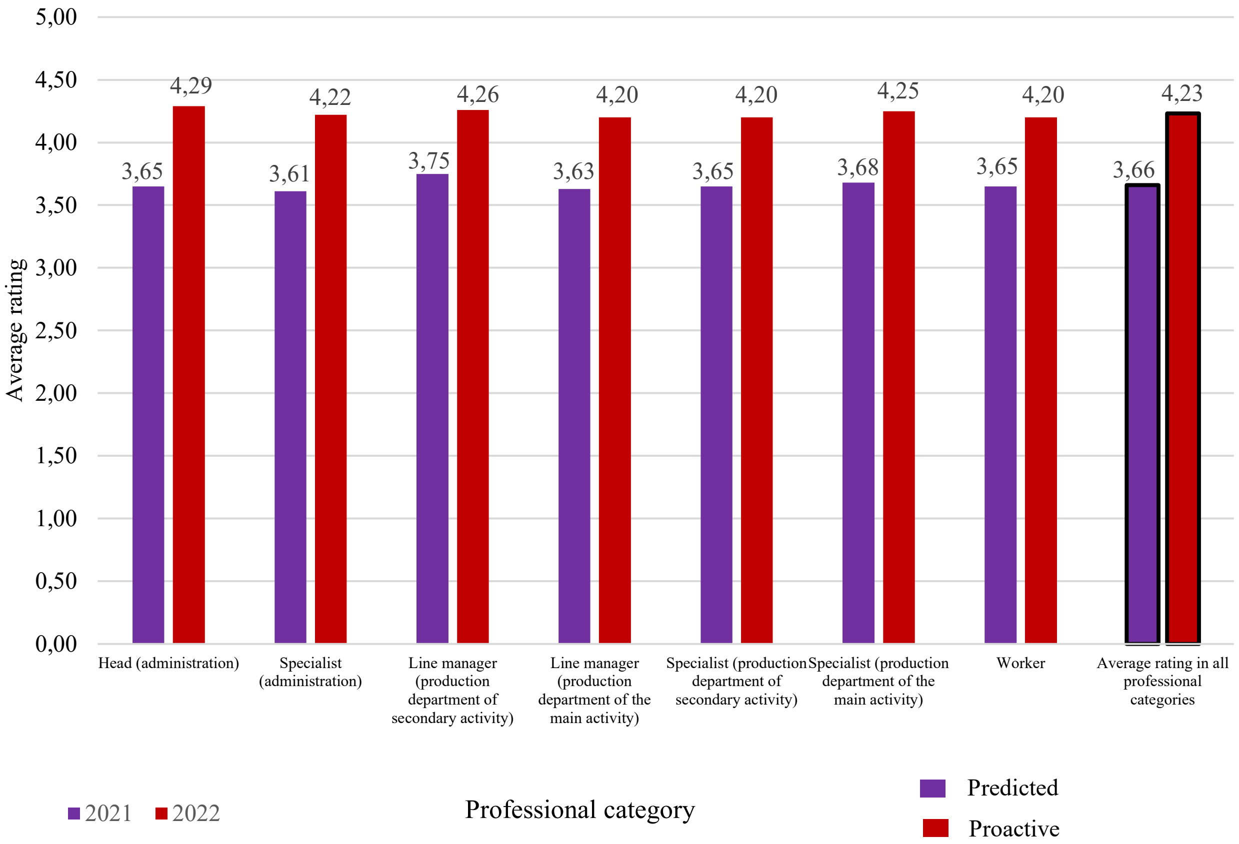


Fig. 4. Comparison of the results of average ISC ratings depending on the professional category of employees of the gas transportation enterprise for 2021 and 2022

It can be seen that in both 2021 and 2022, the professional category of employees did not significantly affect the assessment results, but at the same time, an increase in the ISC level to proactive in each of the professional categories was established. This was due to the implementation of such proactive measures at this enterprise as holding a review-competition of the state of industrial safety and the development of a safety culture with subsequent encouragement of winners and payment of monetary remuneration to employees, installation of video monitors on which videos of violations and injury cases were broadcast, as well as positive and significant events related to IS issues.

According to the algorithm for assessing the ISC level and the results of the survey, histograms of average ratings of all employees for each component of the occupational safety culture were constructed for three age categories: up to 35 years, from 36 to 49 years, from 50 years (Fig. 5).

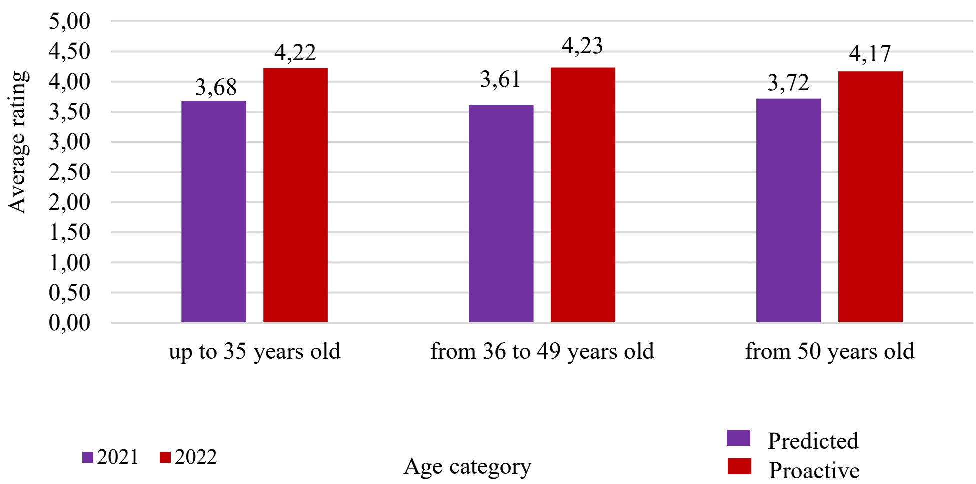
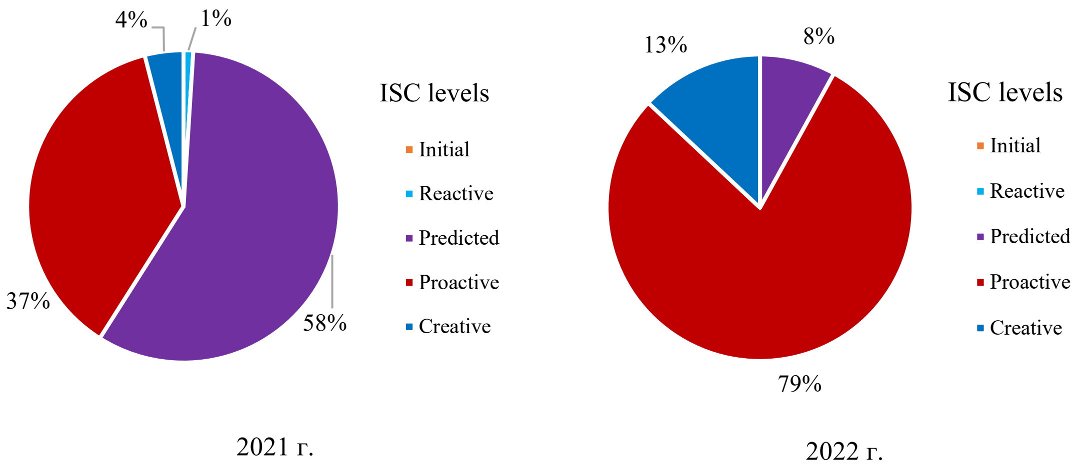


Fig. 5. Comparison of average ratings of the ISC level depending on the age category of employees for 2021 and 2022

As it can be seen in the figure, the employees of all age categories attributed the ISC level in 2022 to proactive, while in 2021 it was predicted. However, the presented data show that there was no dependence of the assessment of the ISC level on the age of employees.

Based on the results of the questionnaire, two pie charts of the distribution of all respondents by the ISC level were formed for comparative analysis (Fig. 6).



a) *b*)

Fig. 6. Comparison of the number of employees of a gas transportation enterprise by the levels of ISC development: *a* — for 2021; *b* — for 2022

Thus, it can be noted that the reactive level disappeared (the average value lied in the range from 1.26 to 2.50). It is important to emphasize that in 2021, 58% of employees estimated the level of industrial safety culture at the predicted level (the average value lied in the range from 2.51 to 3.75), while in 2022 it was only 8%. The share of employees who assessed the ISC level as proactive increased — from 37% to 79% (the average value was in the range from 3.76 to 4.50). An indicative result was an increase in the percentage of employees who rated the ISC level at the creative level — from 4 to 13%.

Based on the results of the focus group interview (questionnaire no. 3) it was revealed that the majority of respondents (70%) were familiar with the motivational program for safe work. Moreover, in their opinion, this program was functioning effectively. At the same time, 70% of the interviewees did not know what share of the bonus was paid to them for safe work and absence of IS requirements violations. However, the vast majority of employees (90%) knew what types of penalties a manager could apply to them for violating the IS requirements. Probably, not all employees understood how the motivation program worked at the enterprise.

The majority of respondents from the focus group (95%) believed that the employer provided a sufficient amount of training in the field of occupational safety and health, but only a quarter of them emphasized that the training took place in an interactive format, followed by practical study of the material presented.

Discussion and Conclusion. The work done by the authors made it possible, first of all, to assess the ISC level at the gas transport enterprise under study, as well as to present a comparative analysis of average values of ISC for all components. In 2022, this value was 4.23 (fourth level), while the average estimate in 2021 was 3.66 (third level) according to the five-level classification of the International Association of Oil and Gas Producers.

Annual monitoring of ISC level allowed us to identify lower components that needed to be paid attention to: motivation and competence, training of employees in the field of IS. In this regard, at the suggestion of the authors of the article, the administration and the IS service of the gas transport enterprise carried out and implemented measures to improve the ISC level.

To ensure motivation for safe work, methods of encouragement for performance and methods of influence for violating the key rules of a gas transportation enterprise were proposed, methodological materials for working with personnel demonstrating risky behavior were developed, and the information about bonus payments was brought to employees through memos and information posters. In order to form and develop competencies in the field of industrial safety, personal obligations of employees in the field of industrial safety have been developed, employees have been trained and will continue to be trained in advanced training programs "Leadership in the field of industrial safety", "Behavioral safety audit. Rules of conduct", "Identification of hazards and risk management in the field of industrial safety", "Analysis of the root causes of accidents. The procedure for their establishment and development of preventive measures", as well as on the topics "ISO 45001:2018 "Occupational health and safety management systems. Requirements with guidance for use", "The procedure for conducting audits of the occupational health and safety management system taking into account the requirements of ISO 45001:2018". The work has been organized aimed at developing risk-oriented thinking among employees of the enterprise.

In the future, it is planned to develop and implement a personnel assessment system that will determine the level of development of critically important personal and leadership qualities of employees and thereby assess the impact of these qualities on ensuring a high ISC level.

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Original article

Model of Multi-Parameter Optimization of Cable Car Characteristics in a Solid Waste Transportation System

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Abstract
Introduction. Modern scientific and applied literature examines the problems of cable cars functioning quite thoroughly. First of all, it concerns ensuring the reliability and safety of traffic, both during operation and during project development.
In addition, the paper considers the relationship of cable cars with the environment and the level of environmental load from this type of transport. A good solution could be the use of mathematical models that can take into account a set of parameters and criteria that characterize the cable car as a system. The same approach would be useful for optimizing technical characteristics of the object. However, there is no description of such a solution in the literature. This gap is partially filled by the presented work. The study aims to create a model of multivariable optimization of cable car technical characteristics for the transportation of municipal solid waste (MSW).
Material and Methods. To clarify the theoretical basis, the literature describing the problems of cable cars and their solutions in general has been studied. Mathematical calculations were justified by a volume of equations that proved their adequacy in determining the useful transport work, load, adjustment of time and speed of cargo movement and other significant parameters of the system under study. When forming the model, we proceeded from the principles of L.S. Pontryagin (needle variation) and Hamilton — Ostrogradsky (kinematics of a certain road segment). Text data about the features of the system elements and their interaction were summarized in tables. The main calculations results were visualized in the form of graphs.
Results. The solution to the problem of optimal control of the cable car on which solid waste was moved was presented. The motion control vector was shown as a vector of optimized technical parameters of the system: speed of movement, rope tension, number and weight of containers. The well-known solution to the optimization problem was reproduced in a general form, which involved determination of a control vector function and its corresponding trajectory with the achievement of a minimum of the target functional. The weak point of the system of differential equations for the realization of the goals of this scientific work was noted. In this regard, it was proposed to consider the investigated section of the cable car as a dynamic system with distributed parameters. The formulation of the multi-criteria optimization problem was described in detail. The advantages of reducing the number of criteria taken into account were listed and the use of the reduction method, which was based on the hierarchical structuring of the system of partial optimality criteria, was justified. Four main elements of the municipal solid waste (MSW) transportation system were considered in interrelation. This was a cable car, a transport and logistics point, a transport and logistics terminal and an environment that generated solid waste. Within the framework of this work, we considered an urbanized environment. The sub-elements of the named elements were listed and 12 directions of their interactions were shown. In detail, within the framework of a three-level hierarchy, four main complex indicators of the complexity of the system under study were described: environment, road, point and terminal. The solution of a multi-criteria optimization problem was shown, calculations were performed for the optimized parameters — the characteristic of the complexity of the road and the characteristic of the terrain. The results of calculations were presented in the form of graphs. Thus, the dependences of the optimized parameters on the weight of the loaded container, the length and speed of the cable car were illustrated.

Conclusions. The main result of the study is an idea of the possibility of a mathematical solution of a multivariable and multi-criteria problem of optimizing two characteristics of a cable car (complexity and terrain feature). The proposed approach allows you to change the hierarchy in the complex of indicators. The results of this scientific work can be used, if necessary, to integrate the road project with neural network models, to work with fuzzy linguistic indicators, to solve applied problems.

Keywords: cable car complexity, cable car environment complexity, transportation of municipal solid waste, multi-criteria optimization

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Научная статья

Модель многопараметрической оптимизации характеристик канатной дороги в системе транспортировки твердых бытовых отходов

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Аннотация

Введение. Современная научная и прикладная литература довольно обстоятельно рассматривает проблемы функционирования канатных дорог. В первую очередь речь идет о вопросах обеспечения надежности и безопасности движения — как во время эксплуатации, так и в процессе разработки проекта.

Кроме того, рассматривается взаимосвязь канатных дорог с окружающей средой, выясняется уровень экологической нагрузки от данного вида транспорта. Хорошим решением могло бы стать использование математических моделей, способных учитывать комплекс параметров и критериев, характеризующих канатную дорогу как систему. Этот же подход был бы полезен для оптимизации технических характеристик объекта. Однако в литературе не представлено описание такого решения. Данный пробел отчасти восполняет представленная работа. Ее цель — создание модели многопараметрической оптимизации технических характеристик канатной дороги для транспортировки твердых бытовых отходов (ТБО).

Материалы и методы. Для уточнения теоретической базы изучена литература, в целом описывающая проблемы канатных дорог и их решения. Математические расчеты обоснованы объемной подборкой уравнений, доказавших адекватность при определении полезной транспортной работы, нагрузки, корректировки времени и скорости перемещения грузов и других значимых параметров исследуемой системы. При формировании модели исходили из принципов Л.С. Понтрягина (игольчатая вариация) и Гамильтона — Остроградского (кинематика определенного отрезка дороги). Текстовые данные об особенностях элементов системы и их взаимодействии сведены в таблицы. Итоги главных расчетов визуализированы в виде графиков.

Результаты исследования. Представлено решение задачи оптимального управления канатной дорогой, по которой перемещают ТБО. Вектор управления движением показан как вектор оптимизируемых технических параметров системы: скорость движения, натяжение каната, число и вес контейнеров. Воспроизводится известное решение задачи оптимизации в общем виде, которое предполагает определение вектор-функции управления и соответствующей ему траектории с достижением минимума целевого функционала. Отмечено слабое место системы дифференциальных уравнений для реализации целей данной научной работы. В этой связи предложено рассматривать исследуемый участок канатной дороги как динамическую систему с распределенными параметрами. Детально описана постановка задачи многокритериальной оптимизации. Перечислены преимущества сокращения количества учитываемых критериев и обосновано применение метода редукции, который базируется на иерархической структуризации системы частных критериев оптимальности. Рассмотрены во взаимосвязи четыре главных элемента системы транспортировки твердых бытовых отходов (ТБО). Это канатная дорога, транспортно-логистический пункт, транспортно-логистический терминал и среда, которая генерирует ТБО. В рамках данной работы речь идет об урбанизированной среде. Перечислены подэлементы названных элементов и показаны 12 направлений их взаимодействий. Детально, в рамках трехуровневой иерархии, описаны четыре главных комплексных показателя сложности изучаемой системы: среда, дорога, пункт и терминал. Показано решение многокритериальной задачи оптимизации, выполнены расчеты по оптимизируем параметрам — характеристика сложности дороги и характеристика местности. Результаты расчетов представлены в виде графиков. Таким образом проиллюстрированы зависимости оптимизируемых параметров от массы загруженного контейнера, длины и скорости канатной дороги.

Обсуждение и заключение. Основной итог исследования — сформировано представление о возможности математического решения многопараметрической и многокритериальной задачи оптимизации двух характеристик канатной дороги (сложность и особенность местности). Предложенный подход позволяет менять иерархию в комплексе показателей. Результаты данной научной работы можно использовать при необходимости интеграции проекта дороги с нейросетевыми моделями, в работе с нечеткими лингвистическими показателями, для решения прикладных задач.

Ключевые слова: сложность канатной дороги, сложность среды канатной дороги, транспортировка твердых бытовых отходов, многокритериальная оптимизация

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Introduction. Modern cable cars are high-tech complexes for passengers and cargo movement. Numerous scientific and applied studies are devoted to them. Technical features of these objects are being studied. The issues of their relationship with the environment are being clarified. Following the trends of recent years, the authors have found out the level of environmental load from this type of transport. The focus of attention is always on ensuring the reliability and safety of traffic — both during operation and during the development of the project.

Many authors and teams have studied the issues of improving technical characteristics of cable cars by improving their designs. The results of such studies have been implemented in passenger and cargo rope transport projects [1–3]. In [4, 5], a different approach to the problem of reliability and safety of operation of the objects under consideration is presented. In this case, the quality of the project is determined by the number of factors that affect the stability of the system. In this regard, it would be advisable to consider the possibilities of multiparametric and multi-criteria optimization of the technical characteristics of cable cars. However, there are no publications on this topic in modern scientific literature.

The work aims to show the possibility of creating a model of multiparametric optimization of technical characteristics of a cable car for the transportation of municipal solid waste (MSW).

Materials and Methods. Within the framework of the presented scientific work, the data from the literature devoted to the issue under study are summarized. One of the approaches to solving the problem is described in [6]. Solid waste is collected in removable containers, compacted, placed in vacuum and delivered by truck to a transport and logistics point. Here the container is moved to the cargo cable car. It connects the transport and logistics point with the transport and logistics terminal, where the container is loaded onto an intermediate decelerating conveyor, removed from the cable car, unloaded, then washed and disinfected. The described scheme assumes environmental control of processes, as well as maintenance and repair.

Let us consider a section of a cable car between two supports (Fig. 1). Let us assume that the supports are located at the same height and at distance l from each other. Between them there can be one or more containers weighing G_{ki} ($i = 1, \ldots, n$) each.

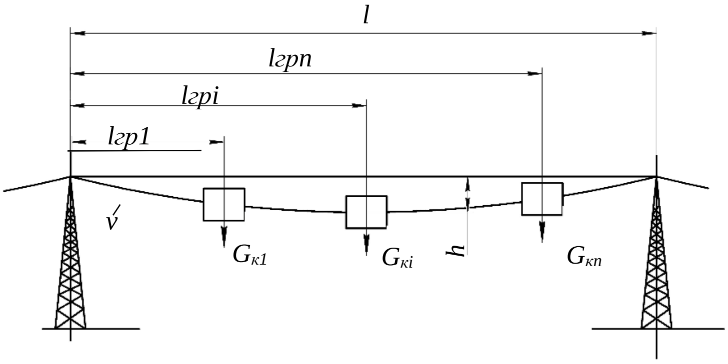

Fig. 1. Diagram of the process of transporting containers on a cable car

On a section of the cable car, the containers with cargo with a total weight of $G_{гр}=\sum_{i=1}^{n}G_{кi}$ are delivered at a certain distance, and then it is an effective transportation A, equal to the product of cargo in tons $l_{гр}$ times the distance in km:

$$A=G_{гр}\cdot l_{гр}=\sum\nolimits_{(i=1)}^{n}(G_{кi}\cdot l_{грi}).$$

Transport work is measured in ton-kilometers. The productivity of the transport process is the useful transport work per unit of time:

$$W=\frac{G_{гр}l_{гр}}{t}$$

where t — time taken to move the load with total weight $G_{гр}$ to the distance of the total load from the support $l_{гр}$; $l_{гр}=\sum\nolimits_{(i=1)}^{n}l_{грi}\,/\,n$.

Value $v=l_{гр}/t$ represents the speed of movement of goods by cable car. In the first approximation, it can be considered equal to the speed of the rope. In general, taking into account the slackness of the rope with containers by value *h*, the speed of movement of goods on the cable car will be slightly less than the speed of the rope.

An effective process is the delivery of as much cargo as possible in less time to a given distance. In our case, loads with a given total weight $\sum G_{гр}$ are moved by a cable car at a distance *l* between two supports. Then the task of increasing efficiency is reduced to minimizing travel time $t_{гр}$:

$$t_{гр}=\frac{\sum G_{гр}l}{v\sum_{i=1}^{n}G_{кi}}\rightarrow\min.$$

When solving problems to reduce the transportation time, such characteristics of the cable car as the speed of movement *v*, the tension of the rope *T*, the number of containers between the supports *n* and the weight of one container with a load $G_{кi}$ vary. Value $G_{кi}$ is assumed to be the same for all containers. Then the task of increasing efficiency is reduced to maximizing:

$$v\sum_{(i=1)}^{n}G_{кi}\rightarrow\max. \qquad (1)$$

The speed of movement of cargo cable cars is limited by standards in the field of industrial safety[1]. The speed parameter is usually limited by the dynamic coefficient μ:

$$\mu=\frac{A_{д}}{A_{ст}},$$

where $A_{д}$ — amplitude of the container vibrations depending on the speed of the rope; $A_{ст}$ — static (or equilibrium) amplitude, i.e. static deformation of the elastic bond (maximum rope sagging) under the action of weight forces of all containers at zero or very low speed of movement the rope.

[1] *Ob utverzhdenii federal'nykh norm i pravil v oblasti promyshlennoi bezopasnosti "Pravila bezopasnosti passazhirskikh kanatnykh dorog i funikulerov"*. Order of the Federal Service for Environmental, Technological and Nuclear Supervision No. 441 dated November 13, 2020. Electronic Fund of Legal and Regulatory and Technical Documents. URL: https://docs.cntd.ru/document/573191373 (accessed 25.09.2023).

Changes in the shape and frequency of vibrations [7] lead to changes in dynamic loads on ropes and other power elements. Overload acting on the container in the vertical direction along the *z* axis:

$$\beta = \frac{P_{д}}{P_{ст}} = 1 + \frac{\ddot{z}}{g},$$

where $P_{д}$ — dynamic load, $P_{ст}$ — static load, $\ddot{z}$ — acceleration of the container in the direction of the vertical z axis.

Therefore, we will proceed from the safety requirements. We take into account the influence of rope tension and parameters from expression (1) on the dynamic coefficient and the magnitude of overloads. In this case, solution to the problem of increasing efficiency requires solution to the optimization problem of the cable system dynamics, which is described by a finite set of parameters. Thus, we are talking about a multiparameter problem.

Results

Formulation of the optimization problem for systems with lumped and distributed parameters. To solve the problem, we apply L.S. Pontryagin's needle variation [8] to the invariant features of the actual motion of a dynamical system.

In the classic formulation of the optimal control problem, the cable car between the supports is considered as a holonomic dynamic system the mechanical connections of which are reduced to geometric ones. For the system under consideration, Hamilton—Ostrogradsky principle [9] is valid, according to which on trajectory $q(t)$, that does not contain kinematic foci:

$$\delta J = \int_0^{t_k} (\delta T + \delta' A)\, dt = 0\,, \tag{2}$$

$$t = 0,\ q(0) = q_0,\ t = t_k,\ q(t_k) = q_k,$$
$$\delta q_0 = \delta q_k = 0\,, \tag{3}$$

where J — target functional; $T = T(q, \dot{q})$ — kinetic energy; $A = \int_{q(0)}^{q(t_k)} Q dq$ — work of generalized forces that depend on generalized coordinates; $q(t) = [q_1, ..., q_n]^T \in R^n$ — vector of specified generalized coordinates; $(t) = [Q_1, ..., Q_n]^T \in R^n$ — vector of generalized forces; $t = [0, t_k]$ — time; δ — symbol of variation; δ*'* — symbol of infinitesimal increment of quantities.

Vector of generalized forces depends on control vector $u(t)$:

$$u(t) \in R^m,\ Q = Q(q, \dot{q}, u, t),\ m \le n. \tag{4}$$

The motion control vector is a vector of optimized technical parameters of the system: speed of movement, rope tension, number and weight of containers.

In general, the optimization problem involves determining the control vector function $u(q, \dot{q})$ and the corresponding trajectory $q(t)$, so that the minimum of the target functional is achieved:

$$J = \int_0^{t_k} F\left(q, \dot{q}\right) dt \to min. \tag{5}$$

Under conditions (2), (3) and control constraints:

$$u \in \overline{G_u}, \tag{6}$$

where $\bar{G}_u$ — closed set of permissible controls in the space of functions $[0, t_k]$ set at a finite time interval; $F(q, \dot{q})$ — sign-constant function.

Let us suppose, in the first approximation, the rope system is modeled as dynamic and consists of a finite number of concentrated masses (containers) connected by elastic constraints. In this case, to solve the optimization problem, it is necessary to determine the laws of speed change $v(t) = \dot{x}(t)$, rope tension $T = f(t)$, the values of the number of containers $n(x, \dot{x})$ and their weight G_{ki} — т such that the target functional J takes the minimum value:

$$J = \int_0^{t_k} \left[\left(x - x_k\right)^2 + \varepsilon \left(\dot{x} - \dot{x}_k \right)^2 \right] dt \to min\,. \tag{7}$$

Initial and terminal conditions for (7):

$$t = 0,\ x\left(0\right) = 0,\ \dot{x}(0) = v_{\min};\ t = t_k,\ x\left(t_k\right) = l, \dot{x}(t_k) = v_{\max}. \tag{8}$$

In addition, taking into account (2), we keep in mind the ordinary differential equations of motion of the dynamical system under consideration. Restrictions are imposed on the speed of movement, the amount of tension, the number and weight of containers:

$$v_{\min} \le v \le v_{\max};\ 0 < T \le T_{\max};\ 1 < n \le n_{\max};\ G_{\min} < G_{ki} \le G_{\max}. \tag{9}$$

In addition, the acceleration of containers in the direction of the x axis, in the transverse direction (along the z axis), as well as the transverse deviations of the i-th container $w(x_i,t)$ along the z axis are limited:

$$\ddot{x}_i(t) \le \ddot{x}_{\max};\ \ddot{z}_t(t) \le \ddot{z}_{\max};\ w(x_i,t) \le w_{\max}. \tag{10}$$

To solve the optimization problem, instead of target functional (7), an extended functional is considered:

$$J = \int_0^{t_k} \left\{ \frac{1}{2} x^2 + \mu \left[\frac{\dot{x}^2}{2} + \int_{x_0}^{x} u\, dx \right] \right\} dt, \tag{11}$$

where μ — Lagrange multiplier.

Let us mention the weak point of constructing a system of ordinary differential equations of motion of the dynamic system under consideration with a variable number of concentrated masses and variable boundary conditions. The fact is that in order to implement this approach, it is necessary to introduce a number of assumptions that reduce the reliability of optimization results. Therefore, we consider the corresponding section of the cable car as a dynamic system with distributed parameters. In this case, to study the dynamic processes of a system with a mobile discrete and distributed inertial load, we use the partial differential equation of transverse rope vibrations reduced to a homogeneous differential equation:

$$\rho(x)\frac{\partial^2 w}{\partial t^2} + 2\rho(x)v\frac{\partial^2 w}{\partial x \partial t} - (T - \rho(x)v^2)\frac{\partial^2 w}{\partial x^2} = 0, \tag{12}$$

where $\rho(x) = \rho_0 + \sum_{i=1}^{n} G_{\textit{гpi}}\delta(x - x_i)$; ρ_0 — mass of the rope length unit; $G_{\textit{гpi}}$ — mass of the i—th concentrated load; $\delta(x - x_i)$ — Dirac function; x_i — coordinate determining the position of the i-th load; T — rope tension; $w(x,t)$ — transverse deviation; v — longitudinal velocity of the rope.

A detailed review of methods for solving optimization problems for dynamic systems with distributed parameters, including hyperbolic systems of form (10) with controlled connections at the boundaries, is given [9]. Most methods are based on the assumption that of all the permissible control actions on the system under consideration, only one corresponds to the optimal state of the process, i.e. solution of differential equation (10). Another assumption is the convexity of the set of permissible controls in the target functional — for example, as in (7). At the same time, for systems with distributed parameters, the absence of optimal control or the presence of multimodal functions in the target functional with multiparametric optimization is acceptable. In addition, the complexity of obtaining the necessary (and, preferably, sufficient) optimality conditions does not guarantee the adequacy of the results of solving a model optimization problem to the optimization goals for a real object. This disadvantage is also characteristic of dynamical systems modeled by ordinary differential equations.

The above proves the relevance of developing approaches that will overcome the shortcomings noted above. It concerns the methods of so-called suboptimal management. These include multi-criteria optimization methods used in decision-making or selection tasks. In this case, they make it possible to consider simultaneously a larger number of parameters of the optimized system in a multidimensional space of criteria (indicators).

Formulation of a multi-criteria optimization problem. Let U — n-dimensional vector of optimized technical parameters of the system (control vector) and $n > 1$. In our case $n = 4$. Vector components: u_1 — speed of movement, u_2 — rope tension, u_3 — number of containers, u_4 — weight of one container. As noted above, restrictions can be imposed on vector U, which is a closed set $\overline{G_u}$ of form (6), which is called the set of acceptable values of the vector of optimized parameters. The dimension of this set is $r \ge n$. Constraints and limiting functions have form (9) and (10).

Let us introduce vector optimality criterion $K(U)$, defined on the set $\overline{G_u}$, in m-dimensional arithmetic space (criterion space) R_e^m. Here $m \ge 1$, i.e. in the limiting case, for $m = 1$ the optimization problem becomes single-criteria, for $m > 1$ — multi-criteria. The components of the vector optimality criterion are particular optimality criteria:

$$K(U) = \{k_1(U), k_2(U), \ldots, k_m(U)\}. \tag{13}$$

They may also be subject to restrictions. This is due to the need to bring to a dimensionless form and a single scale of changes in values, for example, in the proposed model

$$0 \le k_i(U) \le 1,\ i = [1, \ldots, m]. \tag{14}$$

In addition, in the general case, when forming particular optimality criteria, depending on the optimization goal, the values of some particular criteria should be increased, and the values of others should be reduced. Let us note, however, that the task of criterion minimization by introducing an inverse transformation is reduced to the task of maximization. Therefore, let us assume that maximization of all partial optimality criteria is desirable in the developed model.

We also note possible limitations on the value of *m*, i.e. on the number of particular optimality criteria (indicators) formed when solving specific problems. Obviously, one criterion, even a complex one, cannot cover all the requirements. Modern computer technologies make it possible to solve problems with a large amount of data without loss of accuracy, so many researchers maximize the number of particular criteria, use even those factors that practically do not affect the result of optimization. At the same time, an increase in the dimensionality of the system makes it difficult to build and may disrupt the stability of computational algorithms, especially in target functionals with multimodal functions.

From a mathematical point of view, reducing the number of criteria reduces the complexity of computational algorithms and opens up the possibility of a simple graphical interpretation of the results (for example, for two-dimensional or three-dimensional criterion spaces). In addition, the verification of algorithms is simplified. The problem can be reduced to a single-criteria one, and there are many proven methods for solving it. In general, reducing the dimension of the formed system of partial optimality criteria (indicators) greatly simplifies the solution to the optimization problem.

Most often, the method of eliminating duplicate or insignificant indicators is used for reduction. However, it is possible to mistakenly exclude important factors. Therefore, within the framework of the presented work, a reduction method was used based on the hierarchical structuring of a system of partial optimality criteria without their artificial exclusion [10].

So, let us consider the functions (processes) of the system under consideration with an optimized object — a cable car (Fig. 2).

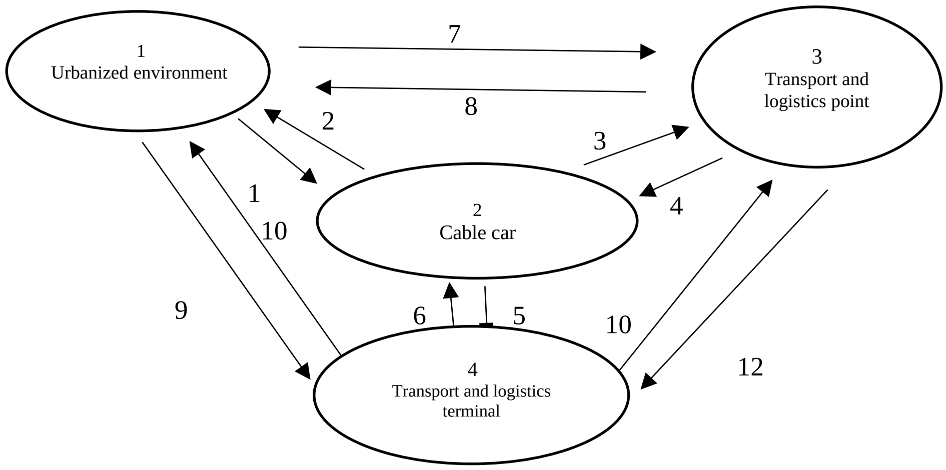

Fig. 2. Functional diagram of the MSW transportation system

Four elements of the MSW transportation system are described in [6].

1. Urbanized environment determines:

– layout of settlements;
– transport infrastructure;
– terrain and landscape;
– natural and climatic conditions;
– weight and volume of generated solid waste;
– time of removal of solid waste.

2. Cable car performs the main function — moving solid waste to the disposal site. The main (including optimized) characteristics of this element of the system:

– type of cable car;
– number of containers on the road and between supports;
– rope tension;
– rope diameter;
– speed of movement;
– step of discrete drives;
– space between the supports.

3. Solid waste is collected and stored for some time at a transport and logistics point. Its main characteristics:
– area;
– height of indoor premises;
– loading and unloading performance;
– dimensions and technical capabilities of conveyors;
– number of empty containers.

4. In the transport and logistics terminal, solid waste is unloaded, moved from the cable car to the disposal site. Emptied containers are sent for washing, storage and inspection. The main characteristics of this element of the system are:
– area;
– height of indoor premises;
– dimensions and technical capabilities of conveyors;
– loading and unloading performance;
– parameters of equipment for washing, drying and disinfection of empty containers;
– number of empty containers.

Table 1 describes the interactions of the elements, which are shown in Figure 2 with numbers from 1 to 12.

Table 1

Interaction of elements of the MSW transportation system by cable car

No	Direction	Interacting elements
1	Urbanized environment — cable car	Volume and weight of solid waste; volume, weight, number of containers; technical characteristics of the road
2	Cable car — urbanized environment	Cable car operation processes; ecological state of the environment; safety indicators of intersected objects (roads, water barriers, buildings, agricultural land, etc.)
3	Cable car — transport and logistics point	Number and weight of empty containers; speed and regularity of arrival of containers at the point
4	Transport and logistics point - cable car	Number and weight of loaded containers; speed and regularity of arrival of containers on the cable car
5	Cable car — transport and logistics terminal	Number and weight of loaded containers; speed and regularity of receipt of containers in the terminal
6	Transport and logistics terminal — cable car	Number and weight of empty containers; speed and regularity of arrival of containers on the cable car
7	Urbanized environment — transport and logistics point	Route length; transport infrastructure; container volume and weight; vehicle load capacity; number of vehicles and containers per vehicle; vehicle speed; speed and regularity of container arrival at the transport and logistics point; climatic conditions
8	Transport and logistics point — urbanized environment	Processes of operation of a transport and logistics point; environmental situation
9	Urbanized environment — transport and logistics terminal	Volume and weight of solid waste; natural and climatic conditions
10	Transport and logistics terminal — urbanized environment	Processes of operation of the transport and logistics terminal; environmental situation
11	Transport and logistics terminal — transport and logistics point	Volume and weight of solid waste; number of empty, excluded and added containers; maintenance and repair processes
12	Transport and logistics point — transport and logistics terminal	Volume, weight of solid waste; number of filled, excluded and added containers

Figure 3 shows the interaction of the main parameters of the system under consideration for a conditional Rostov-on-Don district in the form of a diagram.

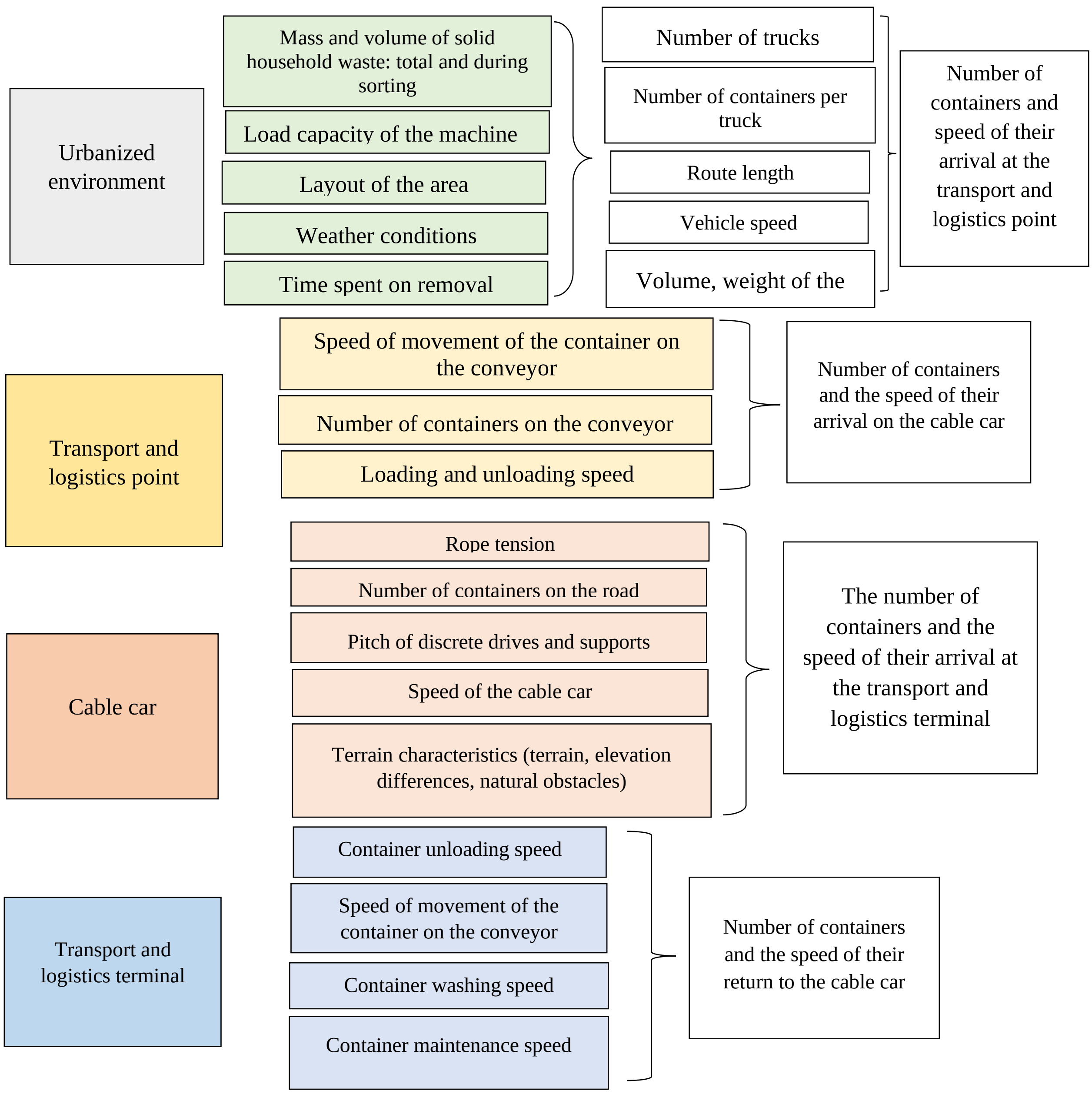

Fig. 3. Scheme of functional interaction of the main indicators of the MSW transportation system from the conditional Rostov-on-Don district

Figures 2 and 3 allow us to build a hierarchy of indicators (Fig. 4).

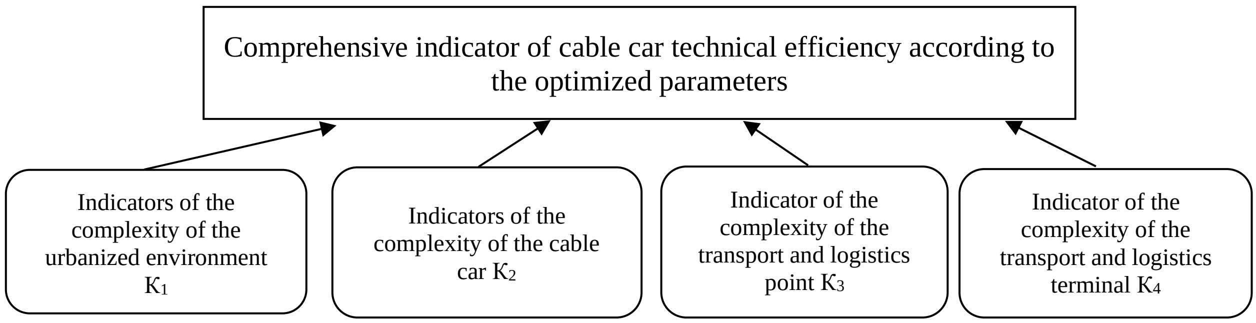

Fig. 4. Hierarchical structure of criteria characterizing the cable car as a system

Tables 2 and 3 show the examples of complex indicators of technical complexity of building and functioning of an eco-friendly system for removal of solid household waste by cargo cable transport in an urbanized environment.

Table 2

Comprehensive indicators of technical complexity of the cable car as a solid waste transportation system

Indicator level			Dimension, unit of measurement
1st	2nd	3rd	
Complexity of an urbanized environment K_1	Layout of the settlement with transport infrastructure K_{11}	Layout of the area K_{111}	Very bad
			Bad
			Average
			Good
			Very good
		State of the transport infrastructure K_{112}	Length of paved streets to the total length of streets
	Terrain and landscape of the area K_{12}		Bad
			Average
			Good
	Characteristics of solid household waste (day) K_{13}	Weight K_{131}	t
		SMW Volume K_{132}	m^3
		Structure K_{133}	Solid
			Liquid
			No classification
	Natural and climatic conditions K_{14}	Temperature K_{141}	C^0
		Wind velocity K_{142}	m/s
		Humidity K_{143}	%
		Number of sunny days in summer K_{144}	Units
	Removal of solid household waste K_{15}	Frequency of solid waste removal K_{151}	Once a week
		Number of trucks K_{152}	Units
		Transportation costs (fuel and lubricants, maintenance) K_{153}	Rub.
		Number of containers per car K_{154}	Units
		Route length K_{155}	km
		Vehicle speed K_{156}	km/h
		Container volume K_{157}	m^3
		Container weight K_{158}	kg
Cable car complexity K_2	Cable car characteristics K_{21}	Cable car length K_{211}	m
		Number of containers on the cable car and between the supports K_{212}^*	Units
		Rope tension K_{213}^*	kN
		Cable car speed K_{214}^*	m/s
		Distance between supports K_{215}	m
		Rope diameter K_{216}^*	mm
		Weight of loaded containers K_{217}	kgr
	Terrain characteristics K_{22}	Height difference K_{221}	m
		Obstacles along the way K_{222}	Bad
			Average
			Good
Transport and logistics point complexity K_3	Layout of a transport and logistics point K_{31}	Occupied area K_{311}	m^2
		Height of indoor spaces K_{312}	m
	Characteristics of loading and unloading operations K_{32}	Number of unloading platforms K_{321}	Units
		Number of loading platforms K_{322}	Units
		Unloading performance K_{323}	Units /hour
		Loading performance K_{324}	Units /hour
	Characteristics of the	Conveyor length K_{331}	m

	conveyor for empty containers K_{33}	Number of containers to be placed K_{332}	Units
		Number of empty containers sent for storage K_{333}	Units
	Characteristics of the accelerating conveyor K_{34}	Conveyor speed K_{341}	m/s
		Conveyor length K_{342}	m
		Load capacity K_{343}	t
		Drive power K_{344}	kW
	Characteristics of the decelerating conveyor K_{35}	Conveyor speed K_{351}	m/s
		Conveyor length K_{352}	m
		Load capacity K_{353}	t
		Drive power K_{354}	kW
Transport and logistics terminal complexity K_4	Terminal size K_{41}	Occupied area K_{411}	m^2
		Height of indoor spaces K_{412}	m
	Characteristics of the decelerating conveyor K_{42}	Conveyor speed K_{351}	m/s
		Conveyor length K_{352}	m
		Load capacity K_{353}	t
		Drive power K_{354}	kWт
	Parameters of the equipment for unloading solid waste from the container K_{43}	Efficiency K_{431}	Units /hour
		Number of tilters K_{432}	Units
		Number of unloading platforms K_{433}	Units
	Parameters of equipment for washing, drying and disinfection of empty containers K_{44}	Line length K_{441}	m
		Number of washing positions K_{442}	Units
		Water pressure K_{443}	MPa
		Characteristics of detergents K_{444}	Bad
			Average
			Good
		Drying speed K_{445}	min
	Characteristics of the conveyor for maintenance and repair of empty containers K_{45}	Conveyor length K_{451}	m
		Number of containers to be placed K_{452}	Units
		Number of empty containers sent for maintenance and repair K_{453}	Units
		Container maintenance K_{454}	Bad
			Average
			Good
	Characteristics of the accelerating conveyor K_{46}	Conveyor speed K_{461}	m/s
		Conveyor length K_{462}	m
		Load capacity K_{463}	t
		Drive power K_{464}	kW
K^* — optimized parameters.			

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Table 3

Intervals of changes in cable car complexity indicators

Level 3 Indicator	Unit of measurement, dimension	Change interval
Cable car length K_{211}	m	1000…50000
Number of containers on the cable car and between the supports K_{212}^*	Units	1…20
Rope tension K_{213}^*	kN	10…15
Cable car speed K_{214}^*	m/s	0.5…5
Distance between the supports K_{215}	m	40…150
Rope diameter K_{216}^*	mm	10…1000
Weight of loaded containers K_{217}	kg	500…1500
Height difference K_{221}	m	0…2000
Obstacles along the way K_{222}	Bad	0…1
	Average	
	Good	

In general, there should be at least two indicators at each level of the hierarchy (with the exception of the topmost one, which represents the target function). When grouping particular criteria at each level, the number of criteria (indicators) in the group can vary from one to some specified maximum value, i.e. $1 \le m \le m_{max}$. At $m = 1$ the indicator of the upper level moves to the lower one without change and vice versa. The maximum value is determined by the dimension of the criterion space and the complexity of constructing a computational optimization procedure in this space. Let us take $m_{max} = 8$.

All criteria (indicators) of the lower level can be measurable and immeasurable. The examples for the first case: "height difference", "total length". For the second case — "relief" (simple, complex, very complex). To describe such criteria, it is proposed to use the methods of fuzzy set theory, i.e. to determine the function of an object belonging to the corresponding set, as in [10].

So, let us formulate the task of multi-criteria optimization to the maximum for each group of partial optimality criteria at all levels. It is necessary to determine the vector function of the optimized system parameters (control vector) U on a closed set $\overline{G_u}$ so that the maximum of the target functional is achieved

$$K(U) \rightarrow \max \tag{15}$$

under condition (13) and constraints (9, 10 and 14).

$\overline{G_u}$ — closed set of permissible controls in the space of specified functions (permissible values of the vector of optimized parameters).

Vector $U^* \in \overline{G_u}$ is the global solution to problem (15) if $K(U^*) \ge K(U)$ for all $U \in \overline{G_u}$.

To solve the multi-criteria optimization problem, we will use scalarization method of vector criterion (13). To this end, we apply the additive function:

$$K_c(U) = \sum_{i=1}^{m} \alpha_i k_i(U). \tag{16}$$

For coefficients α_i the conditions must be met:

$$\alpha_i \ge 0 \text{ при } i = 1,...,m; \sum_{i=1}^{m} \alpha_i = 1. \tag{17}$$

Then initial problem (15) is reduced to finding the maximum of integral indicator (16). In this case, the method of determining the coefficients α_i is especially important. These are the convolution coefficients of vector criterion (13) from the multicriteria space to the numerical axis of scalar criterion (16) with the physical meaning "better" — "worse".

To calculate the convolution coefficients, one can use the methodology proposed in [10]. In this case, fuzzy relations on pairs of objects from the training sample and integral scalar exponent (16) are considered. A computational procedure is constructed for the functional that determines the magnitude of the discrepancy.

After determining the convolution coefficient vectors for all criteria of the hierarchy, it is necessary to find the vector function of the optimized parameters of the system (control vector) U, when additive function (16) reaches the maximum for the criterion of the upper level of the hierarchy (objective function). At the same time, on a set of parameters, the objective function can have several local maxima. Among them, you need to find a global one. There are several computational methods for solving such problems [11]. The so-called evolutionary methods have certain advantages. Some of them are implemented on the basis of a specialized multidisciplinary platform ModeFrontier. To solve this problem, we propose genetic algorithm [12].

Calculations. The optimized parameters of the cable car, as shown in Table 2, are included in K_2 indicator:

$$K_2 = 0,6K_{21} + 0,4K_{22}.$$

K_{21} (cable car complexity characteristic) is determined by the formula:

$$K_{21} = 0,1K_{211} + 0,15K_{212} + 0,15K_{213} + 0,25K_{214} + 0,1K_{215} + 0,1K_{216} + 0,15K_{217}.$$

K_{22} (terrain characteristics), determined by the formula:

$$K_{22} = 0,5K_{221} + 0,5K_{222}.$$

The use of applied software products made it possible to show the results of calculations in the form of graphical dependencies K_{21} and K_2 on the optimized parameters in Fig. 5–8. At the same time, the numerical values of the variable parameters were determined according to Table 2.

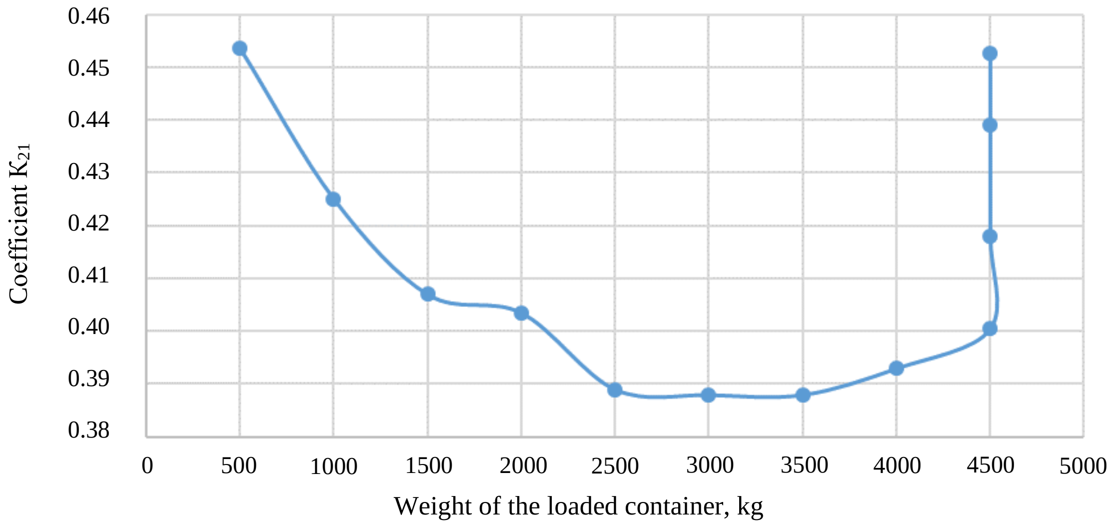

Fig. 5. Dependence of K_{21} coefficient on the weight of the loaded container with a cable car with a length of 20 thousand meters

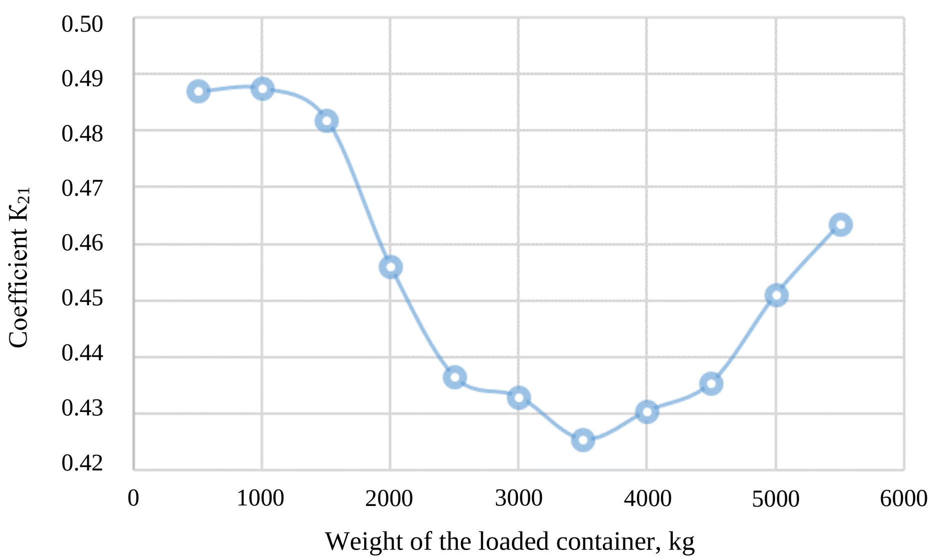

Fig. 6. Dependence of K_{21} coefficient on the weight of the loaded container with a cable car with a length of 40 thousand meters

Figures 5 and 6 demonstrate a pronounced extremum for K_{21} indicator (cable car complexity characteristic) in the weight range of the loaded container 2500–4500 kg. This can be explained by the fact that when using containers with low mass, it is necessary to increase their number to ensure a given performance. As a result, the number of elements of the system increases, that is, it becomes more complicated. The use of containers with a large mass requires the introduction of elements such as additional discrete drives, vibration damping systems, increasing the thickness of the rope, etc., which also complicates the system.

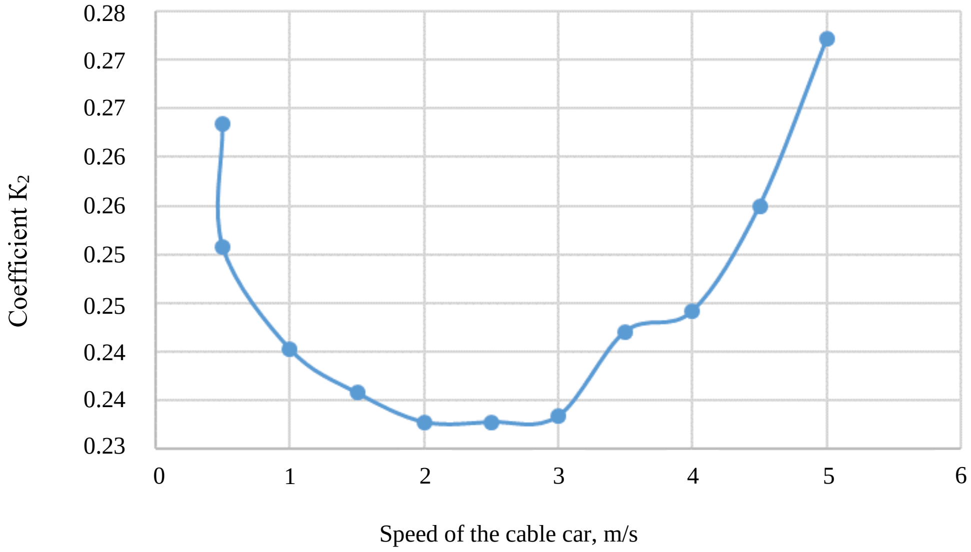

Fig. 7. Dependence of K_2 coefficient on the speed of a cable car with a length of 20 thousand meters

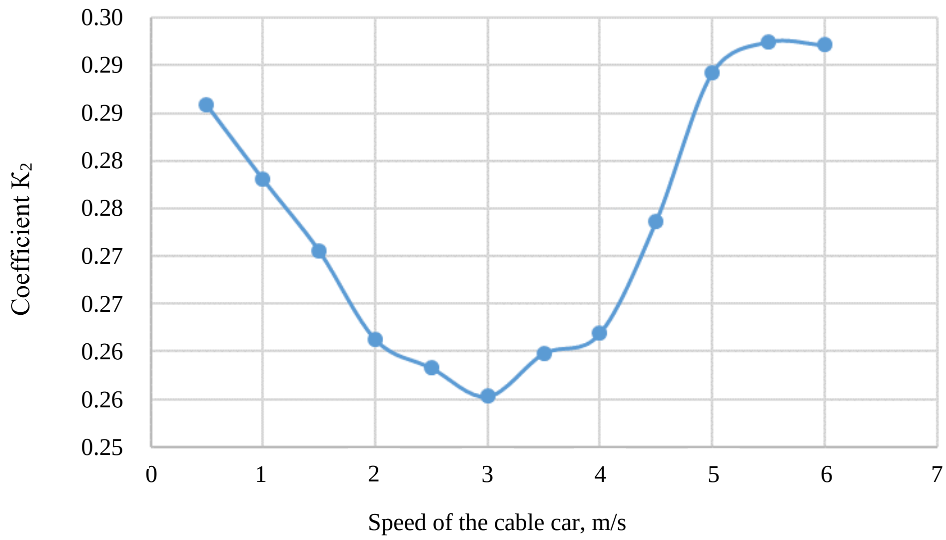

Fig. 8. Dependence of K_2 coefficient on the speed of a cable car with a length of 40 thousand meters

Figures 7 and 8 show that in the speed range of the cable car 1.5...3.5 m/s, K_2 indicator has the lowest difficulty values, since at low speeds more containers are required, and at high speeds additional devices are needed to stabilize movement.

Discussion and Conclusion. The paper considers cable car complexity and terrain features as cable car optimized parameters. In the first case, for optimization, it is necessary to take into account the length of the road, the number of containers, the weight of loaded containers, the tension and diameter of the rope, the speed of the cable car and the distance between the supports. In the second case, the calculation is based on the data on the height difference and possible obstacles along the way. Both groups of these parameters demonstrate the complexity of the cable car in terms of technology and environment (indicator of the 1st level K_2)

A model for solving a multiparametric and multi-criteria problem of optimizing the characteristics of a cable car is proposed. It allows you to change the hierarchy of indicators. This approach can be used if it is necessary to integrate the project with neural network models, to work with fuzzy linguistic indicators, and to solve applied problems.

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Claimed contributorship:

YuV Marchenko, SI Popov: development of the research concept, functional scheme of solid waste transportation, scheme of functional interaction of the system main indicators, development of the hierarchical structure of criteria.

YuV Marchenko: formulation and solution of the problem of multi-criteria optimization for systems with concentrated and distributed parameters.

EV Marchenko: determination of the optimized parameters of a cable car, consideration of the examples of complex indicators of the technical complexity of the construction and functioning of the solid waste removal system by cargo cable transport.

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Заявленный вклад соавторов

Ю.В. Марченко, С.И. Попов — разработка концепции исследования, функциональной схемы транспортировки твердых бытовых отходов, схемы функционального взаимодействия основных показателей системы, разработка иерархической структуры критериев.

Ю.В. Марченко — постановка и решение задачи многокритериальной оптимизации для систем с сосредоточенными и распределенными параметрами.

Э.В. Марченко — определение оптимизируемых параметров канатной дороги, рассмотрение примеров комплексных показателей технической сложности построения и функционирования системы вывоза твердых бытовых отходов грузовым канатным транспортом.

Конфликт интересо: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

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Original article

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Investigation of the Adsorption Properties of Electrically Conductive Pyrolyzed Polyacrylonitrile Modified with Chromium (III) Oxide to Obtain Highly Efficient Gas Sensors

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Abstract

Introduction. Obtaining highly sensitive gas sensors is an urgent task, the solution to which will allow you to accurately and quickly assess changes in the air-gas composition of a given medium. Gas sensors based on metal-containing pyrolyzed polyacrylonitriles (Me-pPAN) are among the cheapest and most environmentally friendly gas-sensitive materials with a fast response. One of the types of sensor materials included in the Me-pPAN list is pyrolyzed polyacrylonitrile (pPAN) modified with a chromium (III) oxide molecule. The reasons for selective adsorption of pPAN and Me-pPAN to pollutant gases, which would allow controlling this process and obtaining sensory materials with increased sensitivity to gases, are not enough studied. Therefore, the aim of this work was to establish the main causes of selective adsorption of semiconductor electrically conductive films by modeling methods in the framework of molecular and quantum mechanics.

Materials and Methods. The authors used modeling methods in the framework of molecular and quantum mechanics (MM2), the density functional theory (COSMO) method and the semi-empirical PM7 method in the MOPAC software package.

Results. MM2 and PM7 methods were used to obtain models of adsorption complexes of "Cr-pPAN – gas-pollutant" systems. Thermodynamic parameters of the system were calculated for standard environmental conditions. The dependence of the adsorption of pollutant gases on the surface of Cr-pPAN on temperature has been established.

Discussion and Conclusion. As a result of calculating the thermodynamic parameters of gas-pollutant–pPAN/Me-pPAN systems and obtaining positive values of Gibbs energies of these systems, it was confirmed that the adsorption of polluting gases on the surface of Cr-pPAN was not a spontaneous phenomenon and was effective at high temperatures. Considering that when chromium (III) oxide was introduced into the pPAN matrix, the charge on nitrogen atoms increased. It could be concluded that a chromium (III) oxide molecule had a positive effect on the semiconductor properties of pPAN. It was found that the adsorption of polluting gases (SO_2 and NO_2) was most likely on the surfaces of pPAN and Cr-pPAN. The results obtained in the work can be used to obtain gas-sensitive materials with specified metrological characteristics.

Keywords: pyrolyzed polyacrylonitrile (pPAN), chromium-containing polyacrylonitrile, quantum chemical model, molecular modeling, adsorption of pollutant gases, semi-empirical method, electron density, thermodynamics of the adsorption process

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Научная статья

Исследование адсорбционных свойств электропроводящего пиролизованного полиакрилонитрила, модифицированного оксидом хрома (III), для получения высокоэффективных сенсоров газов

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Аннотация

Введение. Получение высокочувствительных сенсоров газа является актуальной задачей, решение которой позволит точно и быстро оценивать изменения в воздушно-газовом составе заданной среды. К наиболее дешевым и экологичным газочувствительным материалам, отличающимся быстрым откликом, относятся сенсоры газов на основе металлсодержащих пиролизованных полиакрилонитрилов (Ме-пПАН). Одним из видов сенсорных материалов, входящих в перечень Ме-пПАН, является пиролизованный полиакрилонитрил (пПАН), модифицированный молекулой оксида хрома (III). Причины селективной адсорбции у пПАН и у Ме-пПАН к газам-поллютантам, которые позволили бы управлять данным процессом и получать сенсорные материалы с повышенной чувствительностью к газам, в настоящее время не изучены. Поэтому целью данной работы было установление основных причин селективной адсорбции полупроводниковых электропроводящих пленок методами моделирования в рамках молекулярной и квантовой механики.

Материалы и методы. Использовались методы моделирования в рамках молекулярной и квантовой механики (ММ2), метод теории функционала плотности (COSMO) и полуэмпирический РМ7-метод в программном пакете МОРАС.

Результаты исследования. Методами ММ2 и РМ7 получены модели адсорбционных комплексов систем «Cr-пПАН — газ-загрязнитель». Рассчитаны термодинамические параметры системы для стандартных условий окружающей среды. Установлена зависимость адсорбции газов-загрязнителей на поверхности Cr-пПАН от температуры.

Обсуждение и заключение. В результате расчета термодинамических показателей систем «газ-загрязнителель — пПАН/Ме-пПАН» и получения положительных значений величин энергий Гиббса данных систем потверждено, что адсорбция газов-загрязнителей на поверхности Cr-пПАН не является спонтанным и самопроизвольным явлением и эффективна при высоких температурах. Учитывая, что при внедрении оксида хрома (III) в матрицу пПАН, происходит увеличение заряда на атомах азота, можно сделать вывод о положительном влиянии молекулы оксида хрома (III) на полупроводниковые свойства пПАН. Установлено, что на поверхностях пПАН и Cr-пПАН наиболее вероятна адсорбция газов-загрязнителей (SO_2 и NO_2). Результаты, полученные в работе, можно использовать для получения газочувствительных материалов с заданными метрологическими характеристиками.

Ключевые слова: пиролизованный полиакрилонитрил (пПАН), хромсодержащий полиакрилонитрил, квантово-химическая модель, молекулярное моделирование, адсорбция газов-загрязнителей, полуэмпирический метод, электронная плотность, термодинамика процесса адсорбции

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Для цитирования. Авилова М.М., Золотарева Н.В. Исследование адсорбционных свойств электропроводящего пиролизованного полиакрилонитрила, модифицированного оксидом хрома (III), для получения высокоэффективных сенсоров газов. *Безопасность техногенных и природных систем*. 2023;7(4):97–105. https://doi.org/10.23947/2541-9129-2023-7-4-97-105

Introduction. Rapid monitoring of changes in the air mixture composition in the atmospheric air and in the working area of an industrial enterprise is a necessary measure to assess the impact of production activities on the environment. For these purposes, resistive gas sensors based on modified nanocomposite semiconductor materials are used [1–7]. Gas sensors based on metal-containing pyrolyzed polyacrylonitriles (Me-pPAN) are the cheapest and most environmentally friendly. They are characterized by a rapid response to the presence of pollutants in the air mixture (NO_2, Cl_2, H_2S, CO) among sensor devices [8–11].

In [12–16], to determine the causes of selective adsorption of polluting gases on the surface of pyrolyzed polyacrylonitrile (pPAN) modified with metal oxides, contact processes were simulated using quantum and molecular mechanics methods. In the course of the conducted studies, it was found that one of the promising gas-sensitive materials was pPAN modified with chromium additives (Cr-pPAN) [17]. The fundamental reason for the use of this material was the registration of high indicators of electrical conductivity, more than nine times higher than those for unmodified pPAN [11, 12].

Studies [11, 17], showed that the Cr-modified pPAN surface had a unique feature and selectivity of adsorption with respect to NO_2, Cl_2 and NH_3 under standard environmental conditions. In order to determine the causes of selective gas sensitivity in Cr-pPan, studies were conducted using quantum and molecular mechanics methods [17]. As a result of the research, it was determined that during the adsorption of the pollutant gas on the surface of the sensor-Cr-pPAN, a Van der Waals interaction occurred between the components of the system at the level of 3.5Å-5Å.

According to [18, 19], it is known that the presence of a modifying additive in pPAN contributes to an increase in its semiconductor properties, which was demonstrated in previously published works. According to [17], COSMO method within the framework of the density functional theory confirmed that the introduction of chromium (III) oxide molecules into the pPAN structure led to an increase in semiconductor properties.

Thin-film material based on Cr-pPAN was obtained as a result of polymerization of chromocarbonyl PAN at IR annealing temperatures from 200°C to 400°C [7]. Based on the data of X-ray emission spectroscopy [11], Cr-pPAN films were a pPAN matrix with a chromium (III) oxide molecule embedded in the interplanar spacing.

In previous works [12-17] devoted to the study of the interaction of pollutant gases with the surface of Cr-pPAN, the influence of environmental conditions on adsorption processes was not taken into account. Currently, the causes of selective adsorption of pPAN and Me-pPAN to pollutants, which would allow controlling this process and obtaining sensory materials with increased sensitivity to gases, have not been studied. In addition, an important task is to evaluate the efficiency of the adsorption of polluting gases on the surface of Cr-pPAN under various temperature conditions, the choice of conditions that ensure the most beneficial interaction of components in the "Cr-pPAN – gas-pollutant" system. Therefore, the aim of this work was to determine the main causes of selective adsorption in semiconductor electrically conductive films by modeling methods in the framework of molecular and quantum mechanics, as well as to study the formation process of pPAN modified by a chromium (III) oxide molecule within the framework of the density functional theory. Within the framework of this aim, the main objective of the study for obtaining highly efficient gas sensors was to study the adsorption properties of electrically conductive pyrolyzed polyacrylonitrile modified with chromium (III) oxide.

Materials and Methods. Calculation of thermodynamic parameters of the process of interaction of pollutant gases with Cr-pPAN was carried out using a semi-empirical method within the framework of the MOPAC program.

In the framework of the MM2 method, the energetically advantageous configurations of the initial compounds — chromium (III) oxide in the pPAN matrix, the unmodified pPAN model were obtained. The adsorption complexes (AC) "Cr-pPAN – gas-pollutant" were modeled and the interaction energies were calculated (Fig. 1). Then, in order to predict the adsorption of gases-pollutants (H_2S, NH_3, CH_4, CO_2, NO_2, SO_2, O_3, CO, Cl_2) on the Cr-pPAN surface, thermodynamic parameters of the process were calculated by the semi-empirical PM7 method in the MOPAC program.

When implementing the calculations, the initial structures and models of the "Cr-pPAN – gas-pollutant" adsorption complexes were subjected to preliminary optimization by the method of coordinate descent. At this stage of modeling, the distances from the extreme atom of the adsorbate molecule to the nearest atom of the adsorbent, the modified and/or unmodified pPAN surface, were estimated.

The PM7 method was used to evaluate the spontaneity of interaction and the efficiency of adsorption of pollutant gases on the surface of unmodified pPAN and on the modified surface of Cr-pPAN.

At each stage we calculated the thermodynamic parameters (ΔH, ΔS, ΔG) of the processes at a temperature of 298K according to the following formulas:

$$\Delta H_{\text{adsorbtion}} = \Delta H_{\text{AKC}} - \left(\Delta H_{\text{gas}} + \Delta H_{\text{surface}}\right)$$

$$\Delta S_{\text{adsorbtion}} = \Delta S_{\text{AKC}} - \left(\Delta S_{\text{gas}} + \Delta S_{\text{surface}}\right)$$

$$\Delta G_{\text{adsorbtion}} = \Delta H_{\text{adsorbtion}} - T\Delta S_{\text{adsorbtion}}$$

To construct interaction schemes, charge (q_A, au), spatial (r, Å) characteristics and the amount of charge transfer (Δq, au) in model adsorption complexes were calculated.

Results. The Cr-pPAN cluster model obtained using the MM2 and PM7 methods is represented by a pPAN matrix with a chromium (III) oxide molecule embedded in the interplanar spacing (Fig. 1). The distance between interacting atoms inside the cavity was fixed at the level of 2.0–3.0 Å

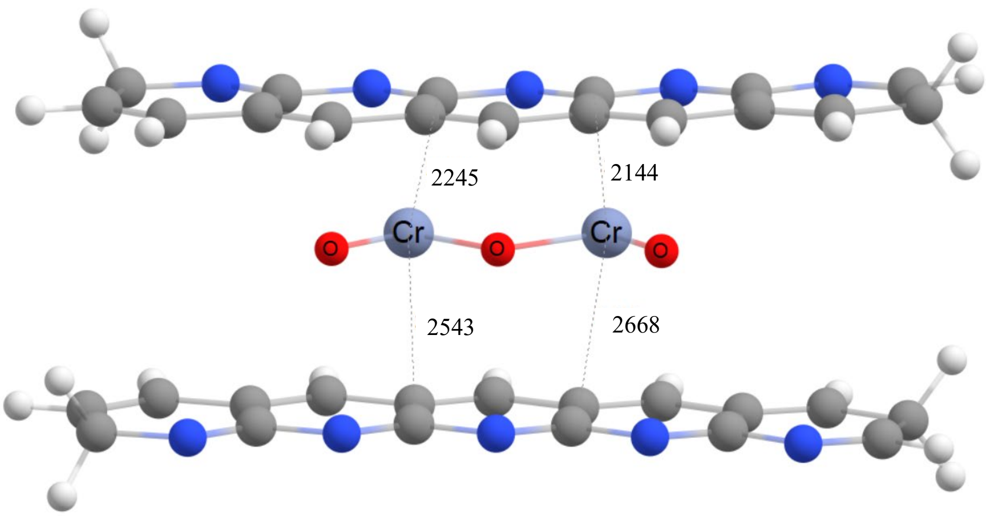

Fig. 1. A model of pPAN cluster modified by a chromium (III) oxide molecule

For example, below is a diagram of the hydrogen sulfide adsorption process:

$$Cr_2O_3(PAN)_2 + H_2S \Rightarrow [Cr_2O_3(PAN)_2\ldots H_2S]$$

Similarly, adsorption schemes for other polluting gases were formed. Figure 2 shows a model using an example of the "Cr-pPAN – SO_2" adsorption complex.

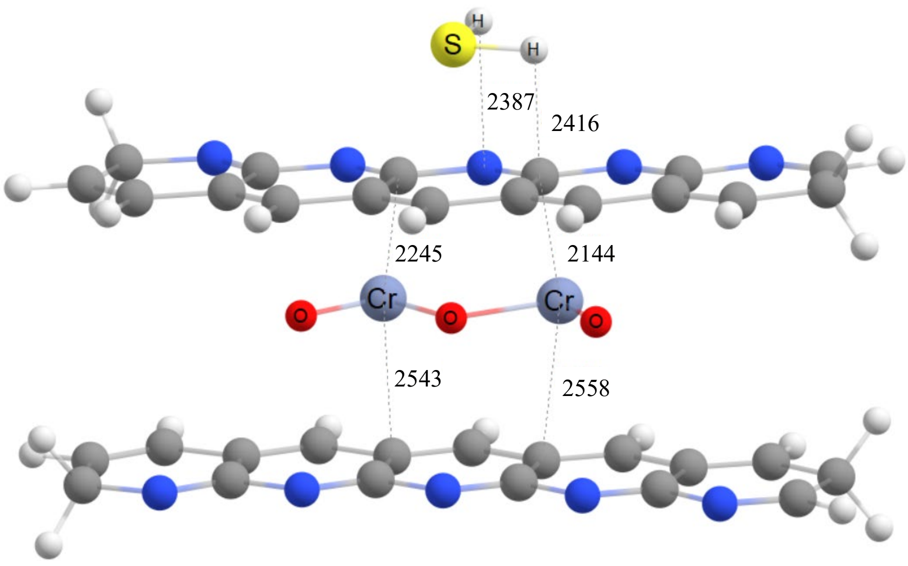

Fig. 2. Model of the "Cr-pPAN – SO_2" adsorption complex

Table 1 provides the calculated thermodynamic parameters of the processes of adsorption of polluting gases on the modified surface, in comparison with the data on the adsorption of these gases on the unmodified pPAN surface.

Table 1

Thermodynamic parameters of the processes of adsorption of polluting gases

Interaction model	Parameters at 298 K		
	ΔH, J/mol	ΔS, J/(mol·K)	ΔG, J/mol
H_2S…pPAN…Cr_2O_3..pPAN	–29.947	–413.888	93.392
NH_3…pPAN…Cr_2O_3..pPAN	–18.258	–295.817	69.896
CH_4…pPAN…Cr_2O_3…pPAN	–15.134	–264.146	63.581
CO_2…pPAN…Cr_2O_3..pPAN	–8.317	–232.773	61.050
NO_2…pPAN…Cr_2O_3..pPAN	–7.354	–232.601	61.961
SO_2…pPAN…Cr_2O_3..pPAN	–2.291	–208.585	59.868
O_3…pPAN…Cr_2O_3..pPAN	–17.887	–222.424	48.395
CO…pPAN…Cr_2O_3..pPAN	–41.647	–412.237	81.200
Cl_2…pPAN…Cr_2O_3..pPAN	–17.176	–217.306	47.580
H_2S…pPAN…pPAN	–1.215	–146.581	42.466
NH_3…pPAN…pPAN	–4.416	–160.438	43.394
CH_4…pPAN…pPAN	–3.197	–161.675	44.982
CO_2…pPAN…pPAN	–2.472	–150.947	42.510
NO_2…pPAN…pPAN	–0.759	–176.267	51.768
SO_2…pPAN…pPAN	–2.393	–181.495	51.693
O_3…pPAN..pPAN	–2.914	–280.125	80.563
CO…pPAN…pPAN	–2.192	–160.186	45.543
Cl_2…pPAN…pPAN	0.341	–153.047	45.949

In the adsorption complex "Cr-pPAN –pollutant gas", the internuclear distance from the extreme atom of the molecule of the studied pollutant gas to the nearest atom on the modified and unmodified pPAN surface was fixed at a level of more than 2.5 Å. These results are in good agreement with those obtained earlier [17] and confirm the presence of Van der Waals interaction occurring in the adsorption complex.

The charge change and electron density redistribution were not observed during the adsorption of pollutant gases on the unmodified pPAN surface (ΔH at the level of –3.0 kJ/mol).

It was established that the adsorption of SO_2 and NO_2 was equally possible both on the modified pPAN surface and on the unmodified pPAN surface, since as a result of the adsorption of these gases, there were no significant changes in the electron density on the surface of Cr-pPAN.

From the presented list of polluting gases, only CO gas shows off-scale results for the modified surface. In the process of adsorption, not only the maximum convergence between interacting atoms was carried out, but also an increase in the charge transfer index (Δq) from 0.3 au for an unmodified surface to 1.2 au for a modified surface.

Discussion and Conclusion. The calculated thermodynamic parameters of the system for standard environmental conditions, presented in Table 1, show that the adsorption of gases cannot be attributed to a spontaneous and self-existing process ($\Delta G > 0$). The general orderliness of the system established during the study of the adsorption processes of polluting gases demonstrates that adsorption is effective at high temperatures.

An increase in the charge in Cr-pPAN and a redistribution of electron density are most effective in the adsorption of polluting gases saturated with hydrogen atoms, namely, H_2S, NH_3, CH_4.

The occurrence of Van der Waals interaction between gases and the surface of Cr-pPAN has been confirmed during the adsorption of polluting gases on the surface of Cr-pPAN. This is justified by the absence of changes in the electron density at the Cr-pPAN polarity during interaction with polluting gases, as well as by the internuclear distance from the extreme atom of the molecule of the studied contaminant gas to the nearest atom of the modified and unmodified pPAN surface exceeding 2.5 Å.

In addition, the study showed that the introduction of chromium (III) oxide into the pPAN matrix contributed to an increase in the charge on nitrogen atoms (before/after: –0.366 au charge / –0.383 au charge). This led to a redistribution of electron density on carbon atoms in cycles (in the ortho position before/after: 0.357/0.428 au charge; in the meta position before/after: –0.159/–0.232 au charge).

Due to the fact that when chromium (III) oxide is introduced into the pPAN matrix, the charge on nitrogen atoms increases, it can be concluded that the chromium (III) oxide molecule has a positive effect on the semiconductor properties of pPAN.

Based on the calculations performed, it is confirmed that the adsorption of polluting gases (SO_2 and NO_2) is most likely on the surfaces of pPAN and Cr-pPAN.

Thus, the theoretical studies carried out allow us to conclude that the modification of pPAN with chromium (III) oxide molecules makes it possible to obtain a promising electrically conductive material with the property of selective adsorption of polluting gases, which can subsequently be successfully used in gas electronics.

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Original article

The Role of Carbides in Forming the Steels Structure and Properties under Pulsed Laser Irradiation

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Abstract

Introduction. At present, in scientific publications, there is no unambiguous understanding and reasoned metal physical justification of the role of the carbide phase of irradiated materials in forming the required structure and achieving a given degree of hardening of surface layers of steels during pulsed laser treatment, especially in the zone of laser hardening from a solid (austenitic) state. The solution to this issue is of great importance, since it allows us to reasonably and purposefully design the required structure of surface layers of products of various functional purposes with high performance properties. The complexity and insufficiently detailed study of the process of structure formation in the surface layers of steels under extreme thermal effects of pulsed laser radiation required a series of metal physical experiments to study the fine structure of steels after high-speed high-temperature hardening. The aim of this article was to obtain, quantify and critically analyze the array of results of metal physical studies and to assess the degree of influence of the carbide phase on the formation of structure and properties of surface layers of steels in the process of pulsed laser hardening in different modes, that is, with and without melting the surface of the samples.

Materials and Methods. In the work, carbon and alloyed tool steels were subjected to surface laser irradiation at a Kvant 16 installation. The radiation power density was 70–200 MW/m^2. Optical, scanning probe and electron microscopy were used in conducting metal physical studies, as well as methods of diffractometric, spectral and durometric analysis of steels before and after laser treatment.

Results. It was shown that laser treatment of steels with a radiation power density of 130–200 MW/m^2 led to a local change in the chemical composition in the laser-fused areas of the spot, partial or complete dissolution of carbides present in the irradiated metal and an increase in the amount of residual austenite in the fused areas up to 40–60%. It was found that on P6M5 steel, the maximum possible hardness of the irradiated zones was achieved by dissolving 30% of carbides, on 9XC, HVG steels — 60–70%. It was shown that under pulsed laser irradiation with q=70–125 MW/m^2, that is, without melting the steel surface, "white zones" formed around carbide inclusions under the influence of thermo-deformation stresses at the boundaries of the "carbide – steel matrix" composition. They had irretrievability, dispersion of the structure and increased hardness (10–12 GPa). It was determined that the maximum hardness of laser-hardened metal in the zones of laser hardening from a solid state was achieved if the "white zones" occupied 40% of the irradiated area of steel. It was found that the dispersion of carbides in this case was 0.5–1.5 microns.

Discussion and Conclusion. The results of the conducted studies indicate that in order to obtain the best combination of hardness and viscosity of the irradiated zones during laser treatment with melting of the surface of steels of different chemical composition, it is necessary to dissolve different amounts of carbides. The dispersed structure of laser-fused steel zones, along with a sufficiently high content of residual austenite, predetermine the possibility of improving the operational characteristics of irradiated materials, especially under conditions of external shock loads.

The analysis of the conducted metal physical studies irradiated without melting the surface of steels allows us to conclude that in order to obtain a high degree of hardening, it is necessary and expedient to ensure the presence of a certain volume of dispersed carbides in the structure of the irradiated steel. The structural composition of "white zones" formed during laser treatment without melting the steel surface contributes to obtaining a unique level of operational properties.

The results of the performed studies contribute to the theory of steel structure formation under conditions of extreme heat exposure and allow for a rational choice of modes of surface laser processing of products and their operability.

Keywords: carbides in steel, laser irradiation, structure, properties

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Научная статья

Роль карбидов в формировании структуры и свойств сталей при импульсном лазерном облучении

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Аннотация

Введение. В современных научных публикациях не существует однозначного суждения и аргументированного металлофизического обоснования роли карбидной фазы облучаемых материалов в формировании требуемой структуры и достижении заданной степени упрочнения поверхностных слоев сталей при импульсной лазерной обработке, особенно, в зоне лазерной закалки из твердого (аустенитного) состояния. Решение этого вопроса имеет большое значение, так как позволяет обоснованно и целенаправленно конструировать требуемую структуру поверхностных слоев изделий разного функционального назначения с высокими эксплуатационными свойствами. Сложность и недостаточно подробная изученность процесса структурообразования в поверхностных слоях сталей при экстремальном тепловом воздействии импульсного лазерного излучения потребовали проведения серии металлофизических экспериментов по изучению тонкого строения сталей после скоростной высокотемпературной закалки. Целью данной статьи явилось получение, количественная оценка и критический анализ массива результатов металлофизических исследований и оценка степени влияния карбидной фазы на формирование структуры и свойств поверхностных слоев сталей в процессе импульсной лазерной закалки на разных режимах, то есть с оплавлением и без оплавления поверхности образцов.

Материалы и методы. В работе поверхностному лазерному облучению на установке «Квант 16» подвергались углеродистые и легированные инструментальные стали. Плотность мощности излучения составляла 70–200 МВт/м^2. При проведении металлофизических исследований использовались оптическая, сканирующая зондовая и электронная микроскопия; методы дифрактометрического, спектрального и дюрометрического анализа сталей до и после лазерной обработки.

Результаты исследования. Показано, что лазерная обработка сталей с плотностью мощности излучения 130–200 МВт/м^2 приводила к локальному изменению химического состава в лазерно-оплавленных зонах пятна, частичному или полному растворению присутствующих в облучаемом металле карбидов и к увеличению количества остаточного аустенита в оплавленных зонах до 40–60 %. Установлено, что на стали Р6М5 максимально возможная твердость облученных зон достигалась при растворении 30 % карбидов, на сталях 9ХС, ХВГ — 60–70 %. Показано, что при импульсном лазерном облучении с q=70–125 МВт/м^2, то есть без оплавления поверхности стали, вокруг включений карбидов под действием термо-деформационных напряжений на границах композиции «карбид – стальная матрица» формировались «белые зоны». Они обладали нетравимостью, дисперсностью строения и повышенной твердостью (10–12 ГПа). Определено, что максимальная твердость лазерно-закаленного металла в зонах лазерной закалки из твердого состояния достигалась в случае, если «белые зоны» занимали 40 % облученной области стали. Установлено, что дисперсность карбидов в этом случае составляла 0,5–1,5 мкм.

Обсуждение и заключение. Результаты проведенных исследований свидетельствуют о том, что для получения наилучшего сочетания твердости и вязкости облученных зон при лазерной обработке с оплавлением поверхности сталей разного химического состава необходимо растворить разное количество карбидов. Дисперсное строение лазерно-оплавленных зон стали, наряду с достаточно большим содержанием остаточного аустенита, предопределяют возможность повышения эксплуатационных характеристик облученных материалов, особенно в условиях действия внешних ударных нагрузок.

Анализ проведенных металлофизических исследований, облученных без оплавления поверхности сталей, позволил сделать вывод, что для получения высокой степени упрочнения необходимо и целесообразно обеспечить присутствие в структуре облучаемой стали определенного объема дисперсных карбидов. Формирующаяся при лазерной обработке без оплавления поверхности стали структурная композиция «белых зон» способствует получению уникального уровня эксплуатационных свойств.
Результаты выполненных исследований вносят вклад в теорию структурообразования сталей в условиях экстремального теплового воздействия, а также позволяют осуществлять рациональный выбор режимов поверхностной лазерной обработки изделий и гарантированно обеспечивать их работоспособность.

Ключевые слова: карбиды в стали, лазерное облучение, структура, свойства

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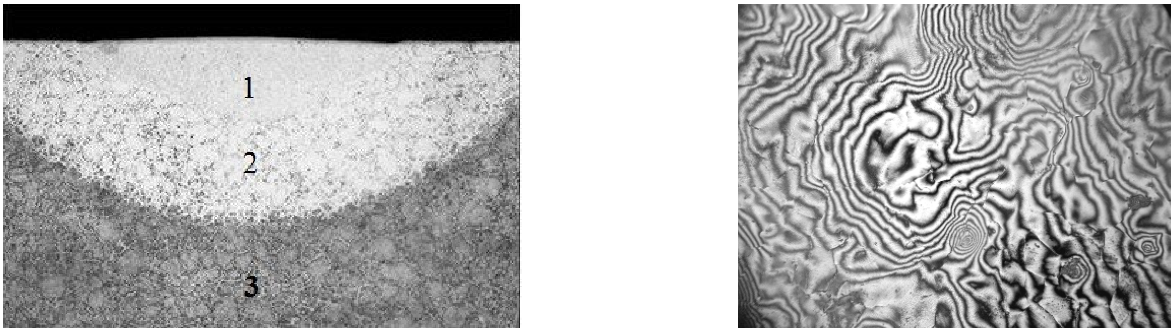
Introduction. During pulsed laser irradiation, the surface layers of the material are subjected to a powerful thermal "shock". Under these conditions, high temperature gradients, concentrations, as well as stress fields appear — thermal, phase, etc. The dissipation of energy acquired by the material can be as follows: partial dissipation of external energy by the dislocation mechanism by local plastic deformation; the dissipation of elastic energy by the mechanism of mass transfer due to the movement of carbon atoms and alloying elements from carbides into solid solutions in contact with them to defects in the crystal structure, etc. [1–4]. It should be noted that mass transfer, which leads to a local change in the chemical composition of laser-irradiated steel zones, plays a particularly important role in the process of structure formation of multiphase steels and alloys containing a significant volume of the carbide phase. The dissolution of carbides, even partial, affects the structure and properties of the surface layers of steels and products in general [5–8].

With high-speed laser processing, that is, in conditions of time scarcity, the effects of carbide dissolution and accelerated mass transfer can be observed only in laser-fused metal zones, at their borders with the initial steel, in thin areas around carbides [9–12]. Emerging microparts with changed chemical composition, structure and properties are of great practical importance, but have not been studied enough. This limits the possibilities for creating a material with a given structure and increased performance in the surface layers of the alloy. Thus, the aim of this study was to determine the influence of the carbide phase on the formation of structure and properties of the surface layers of steels during pulsed laser hardening in different modes, that is, with and without melting the surface of the samples.

Materials and Methods. The analysis of structure formation processes under conditions of high-speed laser heating was carried out on samples of steels U8 (GOST 1435 99), R6M5 (GOST 19265–73), R18 (GOST 19265–73) and others subjected to preliminary volumetric quenching for a martensitic structure and tempering.

Optical, scanning probe and electron microscopy were used in conducting metal physical studies as well as methods of diffractometric, spectral and durometric analysis of steels before and after laser treatment. Pulsed laser irradiation was carried out at a Kvant-16 installation (Russia). Changes in the radiation energy, the degree of beam defocusing (3–6 mm), and the duration of the radiation pulse (1–6) 10^{-3} s allowed varying the radiation power density in a wide range (70–200 MW/m^2). Metallographic studies were carried out on transverse and longitudinal sections on microscopes MIM-7 (Russia) and Neophot-21 (Germany). Studies of fine structure of steels, as well as the determination of chemical composition of the studied zones of irradiated materials were carried out on scanning electron microscopes Hitachi TM-1000 (Japan) and Mira3 (Czech Republic). A diffractometer DRON-0.5 (Russia) was used for X-ray diffraction analysis. Microhardness measurements were carried out on a PMT-3 device (Russia) with a load of 0.49 N.

Results. Metal physical studies showed that the irradiated zones on steels had a heterogeneous structure in the depth of the hardened layer. As it can be seen in Figure 1 *a*, when processing with a radiation power density q=130–200 MW/m^2, a melted quenching zone from the liquid state (1 — LS zone) and a quenching zone from the solid state (2 — SS zone) were observed.

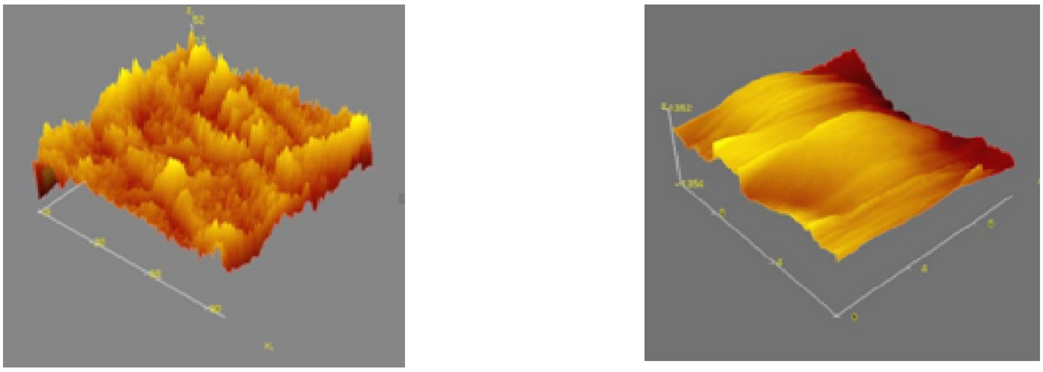


a) *b)*

Fig. 1. Microstructure of irradiated steel R6M5: *a* — 1 — LS zone,
2 — SS zone; 3 — initial steel (×200);
b — convective process in the steel melting zone (interference microscopy) (×300)

Further, the features of formation of structure and properties in both zones of the irradiated spot were considered and described, taking into account the influence of the carbide phase in the steels on these processes.

The LS zone features were its incorrigibility in conventional reagents, the dispersion of the structure and high hardness (8–10 GPa), as well as a noticeable decrease in the volume of the initial carbide phase, even when using optical microscopy. Despite the short exposure time of the laser pulse (10^{-3} s), this was facilitated by the high heating temperature and convective mixing of a thin layer of liquid metal caused by the action of thermostrictive stresses (Fig. 1 *b*). The partial or complete dissolution of carbides was evidenced by the results of studies on a scanning probe microscope (SPM) (Fig. 2), which clearly demonstrated that the dissolution of carbides smoothed the surface relief near carbides due to the mass transfer of their components into the surrounding steel matrix.



a) *b)*

Fig. 2. Structure of surface layers on R6M5 steel:
a — before laser reflow (SPM); *b* — after laser reflow (SPM)

Confirmation of the possibility of partial dissolution of carbides during high-speed laser quenching with melting of the surface of R6M5 steel was also the results of X-ray diffraction analysis shown in Figure 3.

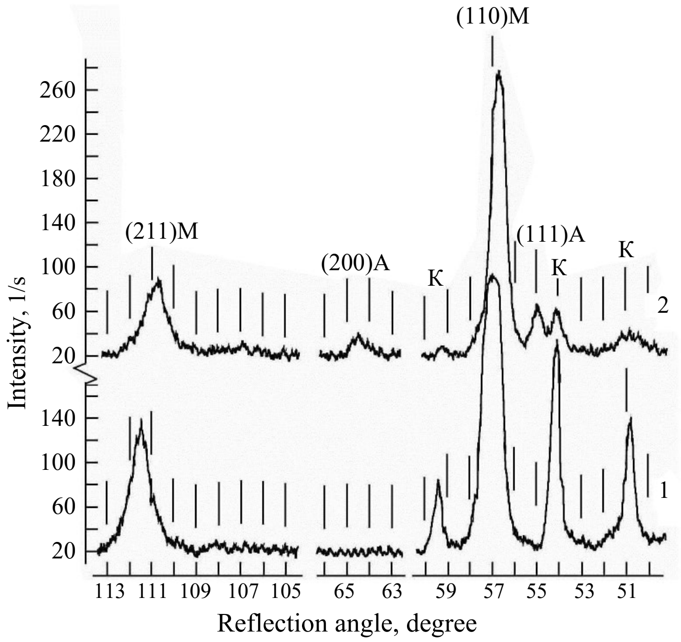
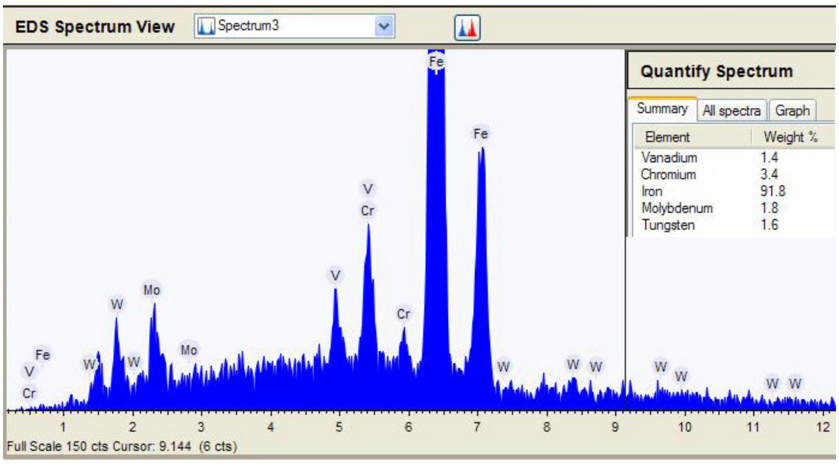


Fig. 3. Phase composition of R6M5 steel before (c. 1) and after (c. 2) laser treatment with surface melting

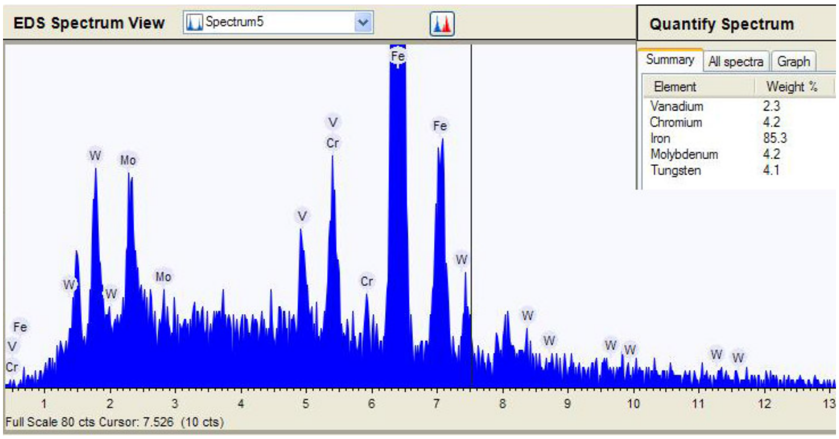
As it can be seen, laser reflow of the steel surface led to a decrease in the height of the carbide phase reflexes (K). Their intensity varied from I=143.24 s^{-1} in the initial steel (Fig. 3, c. 1) to I=65.38 s^{-1} in the LS zone (Fig. 3, c. 2). It can be concluded that the volume fraction of carbides in the LS zone decreased. The angle of the carbides on the radiograph also changed. In the fused zone, carbide reflexes were fixed at angles 2Q=54.1839 compared to 2Q=54.1219 before laser treatment, that is, they shifted to large reflection angles. These results, as well as an increase in the physical expansion of the carbide phase reflexes from 0.6392 mrad for the starting metal to 0.9000 mrad for the LS zone, indicated a change in the stoichiometric composition of carbides, their partial dissolution and an increase in the density of defects of the crystalline structure.

As it can be seen in Figure 3, curve 2, austenite reflexes were also observed on the diffractogram, and martensite reflexes were shifted to smaller reflection angles. This was a consequence of the appearance of areas with high saturation of carbon atoms and alloying elements, and also indicated a high dispersion of the fine structure of the phases of the irradiated metal.

Figure 4 shows the results of determining the local chemical composition of the laser treatment zone of R6M5 steel with surface melting.



a)



b)

Fig. 4. Results of spectral chemical analysis of R6M5 steel samples:
a — in the initial state; *b* — after laser quenching

As a result of changes in the chemical composition, the points of martensitic transformation in the LS zones decreased and a significant amount (40–60%) [13] of residual austenite, characterized by a dispersed structure, remained in them [14–16].

This had a positive effect on the operational properties of irradiated products, especially when exposed to external shock loads.

Figure 5 provides the results of a quantitative assessment of the effect of the volume of dissolved carbides on the degree of hardening of the surface layers of metal obtained during durometric studies of steels irradiated in different modes.

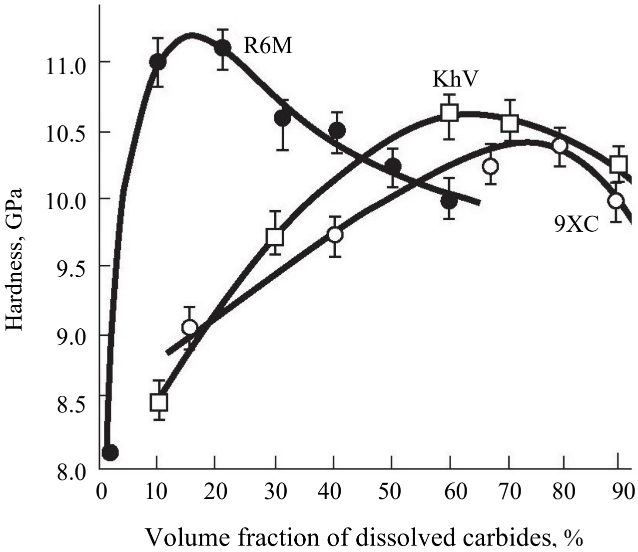
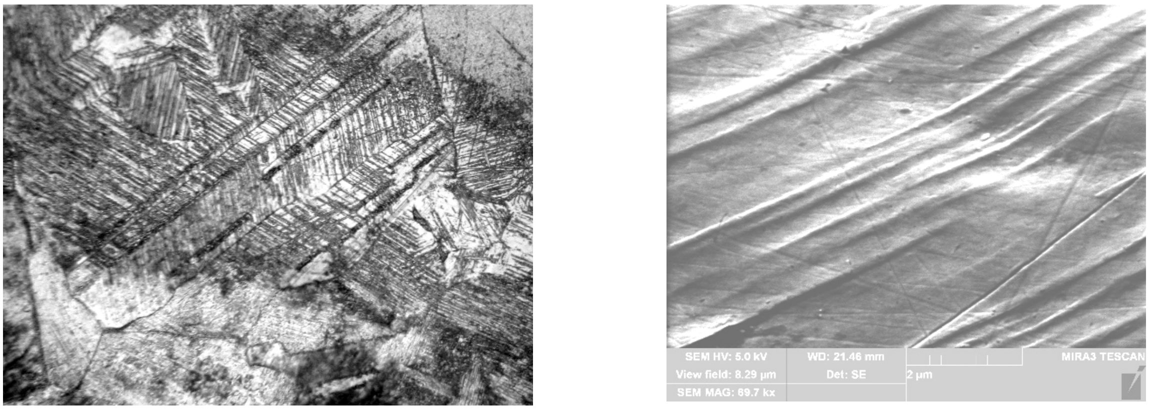


Fig. 5. The effect of the volume of dissolved carbides on the microhardness of irradiated steels

Considering the influence of the carbide phase on the structure of the SS zone, it was necessary to take into account some features of the process of pulsed laser irradiation of materials. They were caused by the appearance of thermostrictive stresses in the irradiated steel zones, the relaxation of which led to local plastic deformation, an increase in density of defects in crystal structure, dynamic return, polygonization and early stages of recrystallization [17, 18]. There was also dispersion of the structure, acceleration of mass transfer of the atoms of the elements and hardening of the metal in the SS zones. Figure 6 provides visual consequences of the influence of local plastic deformation on the structure of polished 12X18H9 steel samples after laser treatment. The traces of deformation in the form of a line or slip bands were clearly visible.



a) *b)*

Fig. 6. Deformation twins after laser treatment of 12X18N9 steel:
a — optical microscopy (×500); *b* — scanning electron microscopy (×10,000)

Figure 7 shows a reconstruction diagram of such characteristic structural features of polygonization and recrystallization processes in laser treatment zones as the formation of a developed substructure, grain refining, grain formation around inclusions, etc.

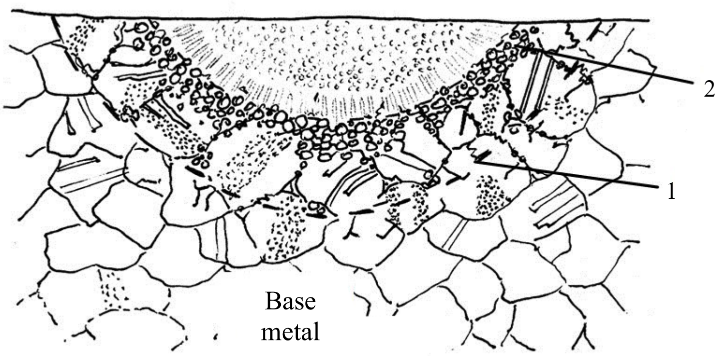
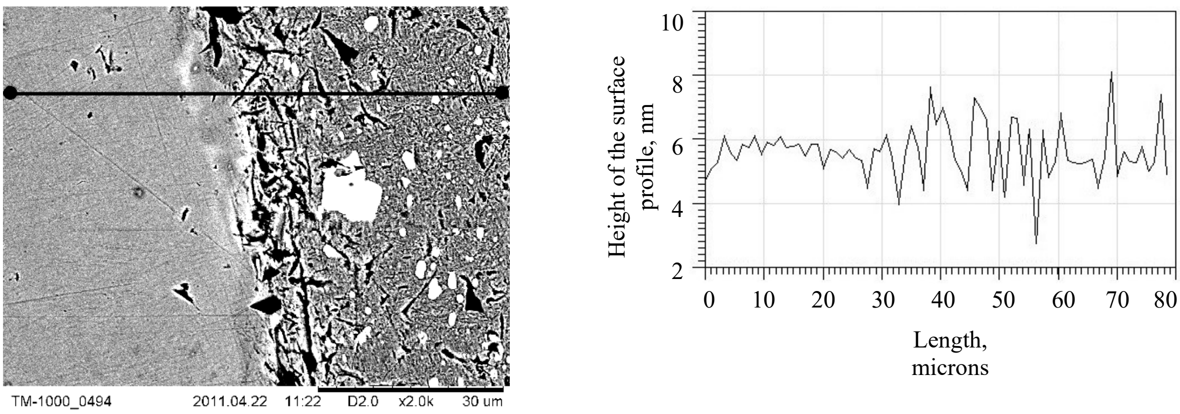
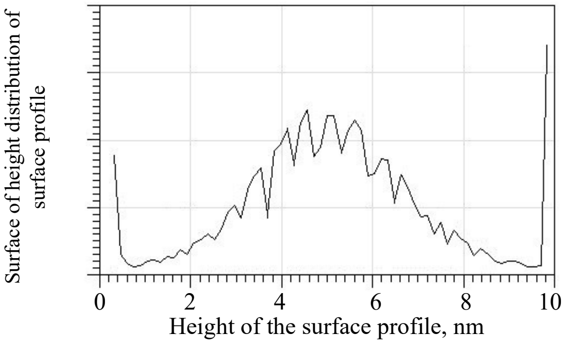


Fig. 7. Diagram of structural features of polygonization (1)
and recrystallization (2) processes in laser irradiation zones

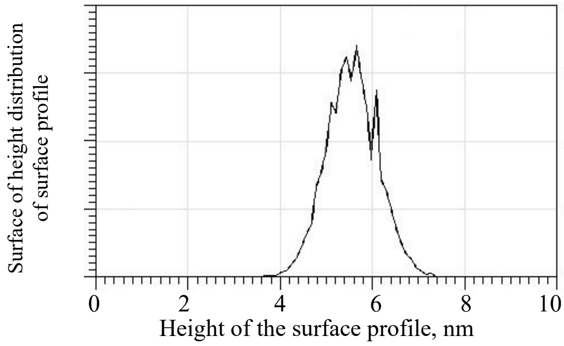
As shown by metal physical studies, the solid state laser quenching zone (SS zone) had a dispersed, poorly etched structure.



a) *b)*



c)



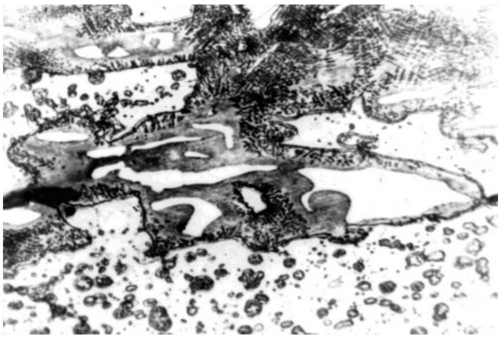
d)

Fig. 8. Microstructure on irradiated R6M5 steel:
a — profilogram of the transition zone from the source metal to the SS zone; *b* — profilogram obtained in the Gwyddion program; *c* — histogram of the distribution of heights of the surface profile in the base metal; *d* — histogram of the distribution of heights of the surface profile in the SS zone

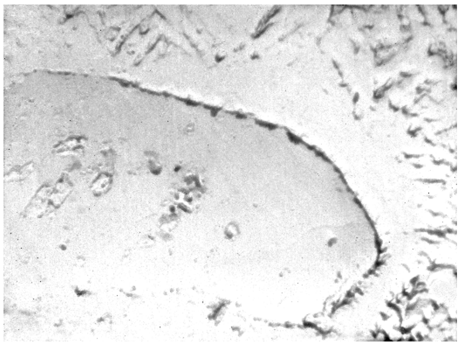
Figure 8 shows the results of the studies of microstructure of irradiated R6M5 steel on a scanning electron microscope.

As it can be seen, carbides were not etched in the SS zone, the surface profilogram was more even than in the base metal (Fig. 8 *b*) and there were no sharp fluctuations in properties at the boundaries in the compositions "carbide – steel matrix".

To confirm the formation of light non-etching shells with an ultradisperse structure ("white zones") around the inclusions of carbides, metallographic studies of the surface of the irradiated without melting zones of R6M5 steel were carried out (Fig. 9).



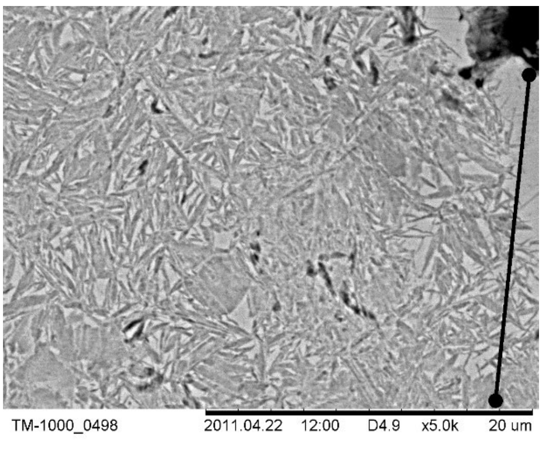
a)



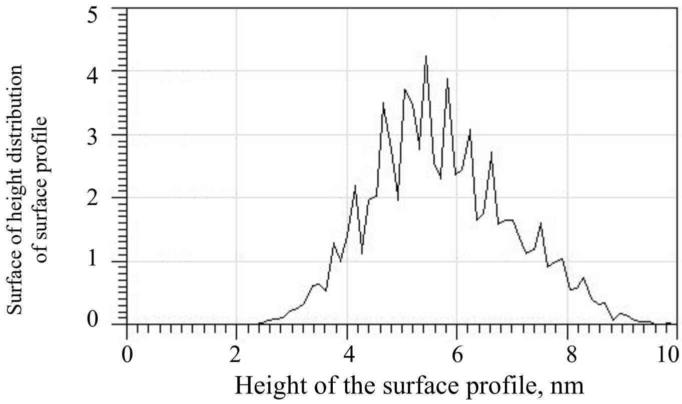
b)

Fig. 9. Boundary dissolution of carbides in irradiated areas of R6M5 steel without melting:
a — metallographic microscope (×800); *b* — electron microscope (×10000)

Studies of the structure of the "white zone" using a scanning probe microscope (SPM) and atomic force microscope (AFM) (Fig. 10 *a*, *c*) showed that martensitic crystals had the form of thin slats 4–7 nm thick and ~150 nm long [19] (Fig. 10 *b*)



a)



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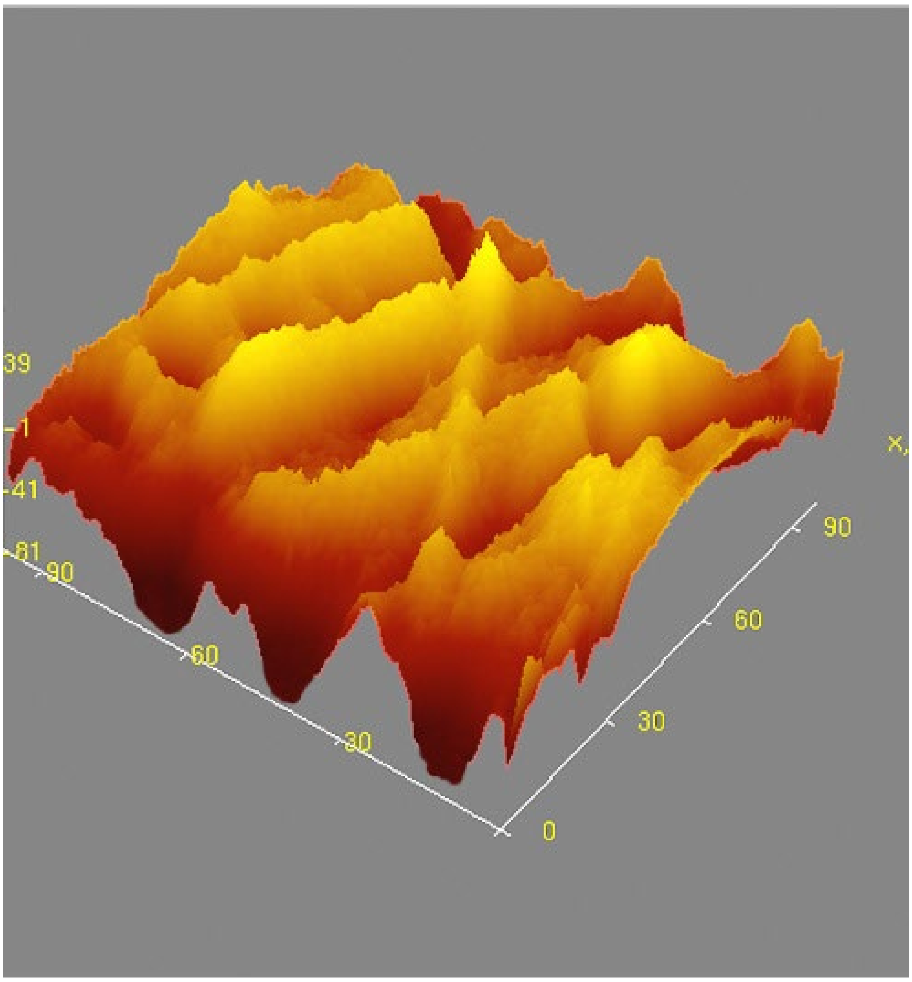

c)

Fig. 10. Microstructure of martensite of laser-quenched R6M5 steel:
a — Hitachi TM-1000 SPM; *b* — distribution of heights of the profile of martensite needles;
c — AFM — image of the structure of the "white zone"

In order to expand knowledge about the fine structure and properties of the SS zone, scratch tests were conducted on a Nanotest installation. A friction probe equipped with a load cell was used, which made it possible to determine the friction force between the indenter and the sample under the influence of gravity of the calibration weights.

Discussion and Conclusion. The listed features of structural state of the melted zone can be associated with the course of dynamic high-temperature plastic deformation during high-speed laser processing. This contributes to the fragmentation of dendritic structure of the irradiated steel zones, accelerates the processes of mass transfer. Confirmation of the above is the result of determining the local chemical composition of the laser treatment zone of R6M5 steel with surface melting. As it can be seen in Figure 4 *b*, due to the dissolution of carbides, the general background of the intensity of reflexes of alloying elements increased in comparison with the original (Fig. 4 *a*) metal.

Based on the results of durometric studies of steels irradiated in different modes shown in Figure 5, it can be concluded that in order to obtain the maximum possible hardness during R6M5 steel laser treatment, it is sufficient to dissolve 30%, and for 9XC, KhVG steels — 60–70% of the initial carbides. The decrease in the hardness of the irradiated zones with an increase in the volume of dissolved carbides was probably due to an increase in the amount of residual austenite under these conditions.

It should be noted that during the operation of irradiated products under the influence of thermo-deformation loads, the decrease in hardness observed in Figure 5 compensated for the large amount of solid dispersed inclusions of hardening carbides released from austenite [20].

The analysis of the results of scanning microscopy of the metal surface showed that in the SS zone the profilogram was more even than in the base metal (Fig. 8 *b*) and there were no sharp fluctuations in properties at the boundaries in the compositions "carbide – steel matrix". This indicates the formation of transitional micro-regions with a changed chemical composition at the borders. As it can be seen in Figure 8 *c*, *d*, the metal in the SS zone was located higher above the plane of the metallographic section. The height of the surface profile on the initial steel was 5.0 nm, and for the laser-hardened zone — 5.8 nm.

The results obtained indicate that the metal regions in the SS zone were more solid and homogeneous, as well as possible partial dissolution of carbide inclusions, which began at the interface between them and the steel matrix. This was confirmed by the formation of light non-etching shells with an ultradisperse structure ("white zones") recorded during metallographic studies around the inclusions of carbides (Fig. 9 *a*), which was especially noticeable at high magnification (Fig. 9 *b*). The formation of such "white zones" during laser processing of steels with a radiation power density of 70–125 MV t/m^2 was facilitated by stresses of various kinds appearing at the boundaries of the "carbide – steel matrix" composition: thermostrictive, stresses due to different thermophysical coefficients in the composition, etc.

Microhardness of these sites was 10-12 GPa. The obtained hardness values corresponded to the hardness of the martensite of alloy steels. It can be concluded that the non-etching edge near the carbide particles was a laser-quenched martensite.

The complex structural picture that was formed around inclusions as a result of stress relaxation was proposed to be described as follows. First of all, due to contact melting, a thin shell of liquid metal was formed in the immediate vicinity of the boundaries of carbides, through which carbon atoms and alloying elements from carbides moved to nearby solid solutions of the irradiated spot. After crystallization, a superhard amorphous-like structure may appear around the carbides. In the rest of the part of "white zones", $\alpha \rightarrow \gamma$ transformation during heating under extreme temperature and force conditions was carried out by shear mechanism. This led to plastic deformation and dynamic polygonization of austenite with the formation of a fragmented substructure. In the process of high-speed hardening in the austenitic edge, $\gamma \rightarrow \alpha$ transformation occurred with the inheritance of the fragmented structure of austenite by martensite.

The results of metallographic and durometric studies showed that the maximum hardness of laser-hardened metal in the SS zones was achieved if the "white zones" occupied 40% of the irradiated area of steel. The dispersion of carbides should be 0.5–1.5 microns.

It was established that when the indenter scratched the base metal of R6M5 steel, friction force fluctuations were observed caused by the movement of the indenter through an inhomogeneous structure consisting of phases with different hardness. There were no significant friction force fluctuations in the SS zone of the laser-irradiated metal. It can be concluded that the SS zone was relatively homogeneous in structure and hardness, and its hardness was much higher than the hardness of the base metal. This was evidenced by the values of the friction force of about 17 MN in comparison with 11 MN for the base metal.

The analysis of the conducted metal physical studies indicates that laser treatment with a radiation power density of 130–200 MW/m^2, that is, with the melting of the surface of steels of different chemical composition, obtained the best combination of hardness and viscosity of the irradiated zones when dissolving different amounts of carbides. Due to the fixed dispersed structure of laser-fused steel zones, along with a sufficiently high content of residual austenite in them, it became possible to increase the operational characteristics of irradiated materials, especially under conditions of external shock loads.

Metal physical studies of irradiated steels, with a radiation power density of 70–125 MW/m^2, that is, without melting the surface, allowed us to conclude that in order to obtain a high degree of hardening in this case, it is necessary and advisable to ensure the presence of a certain volume of dispersed carbides in the structure of the irradiated steel. The structural composition of the "white zones" formed during laser treatment without melting the steel surface contributed to obtaining a unique level of operational properties.

The results of the research made a contribution to the theory of steel structure formation under conditions of extreme heat exposure, and also made it possible to make a rational choice of modes of surface laser processing of products of various functional purposes to ensure their operability.

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Original article

Wear Reduction in Heavily Loaded Units of Transport Vehicles

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Abstract
Introduction. The pivot assembly provides connection between the rotating and non-rotating parts of machines and mechanisms such as cranes, excavators, trailers, railway rolling stocks. In relation to rolling stock, it connects the load-carrying part of the car with the bogie and is one of the most critical and wear-out friction units. Its technical condition affects the intensity and form of wear of the surfaces themselves, the amount of resistance to rotation of the bogie when the car moves in curved sections of the track, the amplitude of the lateral rocking of the car, the intensity of wear of the wheel flanges and, as a consequence, the safety of operation of the rolling stock as a whole. Until now, periodic grease is used for this unit, which, even with a short mileage, manages to be squeezed out of the contact zones and, thereby, creates conditions for the predominance of dry friction. Until now, various proposals to solve this problem have not found application in mass production for a number of reasons, and therefore the search for ways to reduce wear in the pivot assembly of cars is still relevant. This study proposes a solution to this problem that does not require structural changes to the pivot assembly itself. The aim of this work was to develop a technologically advanced anti-friction coating with good adhesion, which will be applied to the surface of a replaceable disk installed between the rubbing surfaces of the pivot assembly during scheduled repairs of the car chassis. This approach will reduce the friction force and wear rate in the unit when lubrication shortage occurs due to squeezing out of the grease.
Materials and Methods. Antifriction characteristics of the developed coating was observed on a friction machine providing specific loads on the test sample up to 5000 N and a sliding speed from 0.13 m/s. The samples were examined by scanning electron microscopy (FEI Quanta 200 microscope). SEM images were acquired in a back-scattered electron (BSE) mode using a semiconductor detector. To analyze the elemental composition of beam samples, an energy dispersive spectrometer (EDAX Element EDS system) was used.
Results. A three-layer functional phosphorus-containing composite coating of the surfaces of the unit was developed, which made it possible to significantly reduce the coefficient of friction and, as a consequence, the intensity of wear of the pivot unit surface during dry friction. The optimal conditions for obtaining composite coating layers were determined. The influence of the thickness of each layer and the conditions for its production on its functional characteristics was studied.
Discussion and Conclusion. The proposed solution is manufacturable and, with appropriate adaptation, can be used to reduce wear in any open pivot assembly without radically changing its design. The methods for producing coating layers are accessible and technologically advanced for serial use.

Keywords: rail rolling stock, pivot assembly, open friction assembly, composite multilayer coating, wear reduction

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Научная статья

Снижение износа высоконагруженных узлов транспортных средств

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Аннотация
Введение. Опорно-поворотный узел обеспечивает связь между поворотной и неповоротной частью машин и механизмов кранов, экскаваторов, автоприцепов, железнодорожных подвижных составов. Применительно к подвижному составу он соединяет грузонесущую часть вагона с тележкой и является одним из наиболее ответственных и быстроизнашивающихся узлов трения. Его техническое состояние влияет на интенсивность и форму износа самих поверхностей, величину сопротивления повороту тележки при движении вагона на криволинейных участках пути, амплитуду боковой раскачки вагона, интенсивность износа гребней колес и, как следствие, на безопасность эксплуатации подвижного состава в целом. До сих пор для данного узла применяется периодическая консистентная смазка, которая даже при небольшом пробеге успевает выдавиться из зон контакта и тем самым создать условия для преобладания сухого трения. До настоящего времени различные предложения по решению этой проблемы не нашли применения в серийном производстве по ряду причин, и поэтому поиск путей снижения износа в опорно-поворотном узле вагонов до сих пор является актуальным. В данном исследовании предлагается решение этой проблемы, не требующее конструктивных изменений самого опорно-поворотного узла. Целью данной работы является разработка технологичного антифрикционного покрытия с хорошей адгезией, которое будет нанесено на поверхность сменного диска, устанавливаемого между трущимися поверхностями шкворневого узла во время плановых ремонтов ходовой части вагона. Такой подход позволит снизить силу трения и интенсивность износа в узле при наступлении смазочного голодания из-за выдавливания консистентной смазки.
Материалы и методы. Антифрикционные характеристики разработанного покрытия определялась на машине трения, обеспечивающей нагрузки на исследуемый образец до 5 000 Н и скорости скольжения от 0,13 м/с. Образцы исследовались методом сканирующей электронной микроскопии (микроскоп FEI Quanta 200). СЭМ-изображения получены в режиме регистрации обратно-рассеянных электронов (BSE) с помощью полупроводникового детектора. Для анализа элементного состава образца использовался рентгеновский энерго-дисперсионный спектрометр (EDAX Element EDS System).
Результаты исследования. Разработано трехслойное функциональное фосфорсодержащее композиционное покрытие поверхностей узла, позволяющее существенно снизить в нем коэффициент трения и, как следствие, интенсивность износа шкворневого узла из-за сухого трения. Определены оптимальные условия получения слоев композиционного покрытия. Изучено влияние толщины каждого слоя и условий его нанесения на функциональные характеристики.
Обсуждение и заключение. Предложенное решение отличается технологичностью и при соответствующей адаптации может быть использовано для снижения интенсивности износа в любом открытом опорно-поворотном узле без кардинального изменения его конструкции. Методы получения слоев покрытия доступны и технологичны для серийного применения.

Ключевые слова: рельсовый подвижной состав, шкворневой узел, открытый узел трения, композиционное многослойное покрытие, снижение износа

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Introduction. In railway transport, one of the most responsible and high-wearing friction units is the pivot assembly connecting the body to the bogie. A well-known problem of this unit is the squeezing out of lubricant from it, even with minor runs, followed by contact of surfaces in dry friction mode and the corresponding wear intensity [1].

Currently, planned restoration of worn-out pivot assemblies annually results in huge sums, even without taking into account losses from idle cars and the costs of their unscheduled repairs. If we take into account the fact that there are more than 1.3 million cars in circulation in our country, then the task of reducing friction and wear in this unit is urgent. This problem is sectoral on the scale of all industrially developed countries of the world [2]. To date, there are various approaches to solving this problem, which can be broadly divided into several principal groups.

The first group includes methods based on changing the design of the unit in order to increase the diameter of the support surface and, as a result, reduce specific loads. The disadvantage of this approach is the exclusion of interchangeability of unit elements during mass repairs. The second group includes methods in which replaceable inserts made of various polymer wear-resistant materials are installed between the rubbing surfaces in the form of a round pocket with annular grooves at the bottom for the accumulation of grease. The presence of a replaceable element reduces the cost of repairing this unit. However, in severe operating conditions of the pivot assembly, polymer materials have a very short service life. The third group includes methods in which replaceable inserts made of high-strength steels, for example, manganese steel, are installed between the rubbing surfaces. However, this approach does not exclude the wear of the surface of the pivot assembly itself. After the inevitable squeezing out of viscous lubricant, wear intensity will be determined by the ratio of hardness of the contacting surfaces of the removable disk and the main unit. The fourth group of methods includes methods for improving heat treatment of contacting surfaces.

Another solution to eliminate increased friction in the pivot unit is to install a less rigid disk with holes distributed over its entire surface between the rubbing surfaces. The perforation in the disc is filled with solid grease. The supply of lubricant to the friction surface in this case is adaptive and is determined by the intensity of wear on the surface of the replaceable disk (Fig. 1) [3].

Since squeezing out of viscous lubricant and periodic contact of surfaces in the dry friction mode in this unit is inevitable, it is proposed to increase the durability of this unit by reducing the intensity of wear by installing a replaceable disk with a durable and technologically advanced antifriction coating between the friction surfaces. With this approach, lack of lubrication during squeezing out of regular grease will have less effect on the intensity of wear and, as a result, prolong the durability of this unit [4–6].

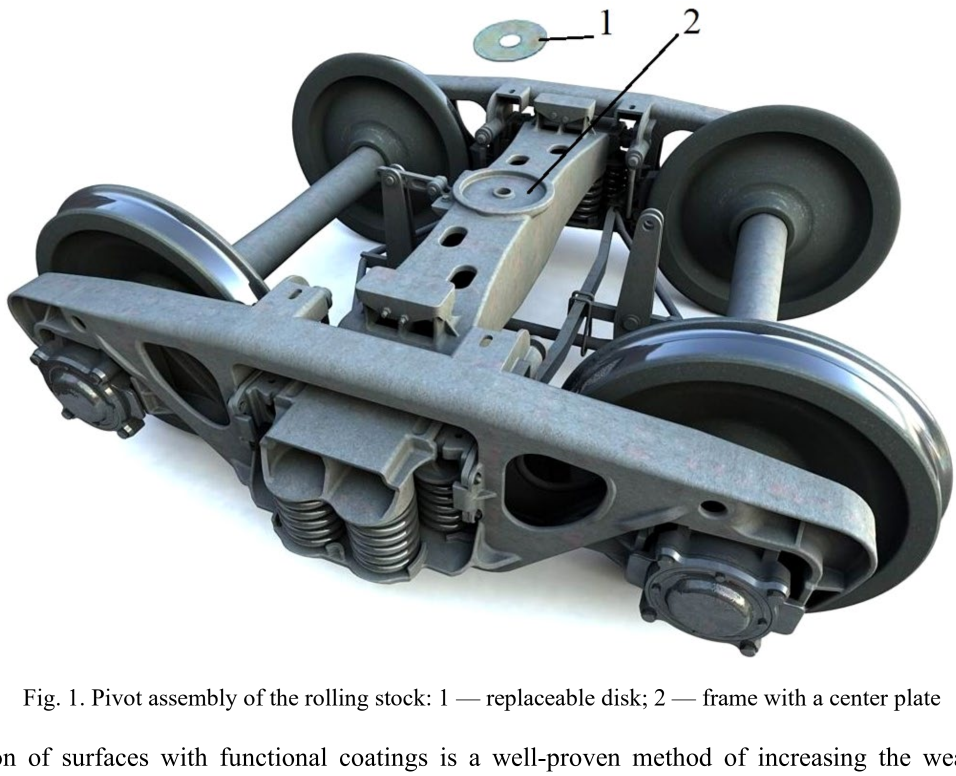


Fig. 1. Pivot assembly of the rolling stock: 1 — replaceable disk; 2 — frame with a center plate

Modification of surfaces with functional coatings is a well-proven method of increasing the wear resistance of components operating under difficult conditions — under high loads, absence or interruptions in the supply of lubricant to the friction zone, in aggressive abrasive media, etc. [7–13].

In this study, the aim was to develop a coating that provides a low coefficient of friction on surfaces, as well as creating conditions for rigid dynamic contact of reliable adhesion with the material of the coated product.

Materials and Methods. It was decided to solve this problem by developing a three-layer coating from a combination of several layers of a phosphorus-containing composite [14]. In order to comply with the specified requirements, the influence of the thickness of each layer and the conditions of its manufacture on its functional characteristics was studied. The coating was applied in layers. Chromium steel was chosen as the material for the base, i.e. the replaceable disc.

The first layer to be applied consisted of a composite nickel-phosphorus compound modified with molybdenum disulfide. Its task was to ensure high adhesion to the substrate. This layer was obtained by chemical deposition. The subsequent layer was made on the basis of a phosphate binder [14, 15], the task of which was to ensure the binding of the first layer with the third and increase corrosion resistance due to the fact that the bogie pivot was an open friction unit. In order to reduce the cost and increase the manufacturability, the layer was obtained by several simple and technological methods (spraying, dipping and spreading), followed by a comparative assessment of its functional properties. The third layer, which provided antifriction properties, was also obtained by spraying and spreading, followed by a comparative assessment of its properties [14, 15].

The adhesion quality of the layer to the previous one was assessed by the results of the cross-cut test by an adhesion tester[1]. The thickness of each layer was measured by a combined-action thickness gauge. The antifriction parameters of the third layer were determined using an AI 5018 friction machine. The analysis of the surface of the layers was carried out by scanning electron microscopy on a FEI Quanta 200 microscope. SEM images were obtained in the backscattered electron (BSE) registration mode using a semiconductor detector. An X-ray energy dispersion spectrometer EDAX Element EDS System was used to analyze the elemental composition of the sample.

Statistical processing of the results of the experimental studies was carried out by computer methods of processing the results of an engineering experiment.

In the course of the research, the conditions influencing the final parameters of the resulting coating were determined. The following influence was investigated:

– of the temperature of the solution on the thickness of the resulting coating;

– of the thickness of the third layer on its adhesion to the previous one;

– of the thickness of the third layer and the conditions for its production on the value of its friction coefficient.

The first layer (nickel-phosphorus coating) was obtained by chemical deposition. To ensure the sedimentation stability of the modifiers present in the chemical precipitation solution, a PE-6110 magnetic mixer with a heating function was used. The deposition process of this layer took place under conditions of 90-92°C. The adhesion of the coating to the substrate was evaluated according to the standard procedure for such cases[2]. The second layer (phosphate coating), according to the idea, was applied by three different methods: dipping, spreading and spraying [14]. The third (antifriction) layer was obtained by several methods — spraying and spreading over a phosphate binder [15].

Since the layers of the resulting composite coating are not operable without heat treatment, the effect of the heat treatment modes of the layers on their final properties was investigated, followed by the selection of the optimal mode for each of them.

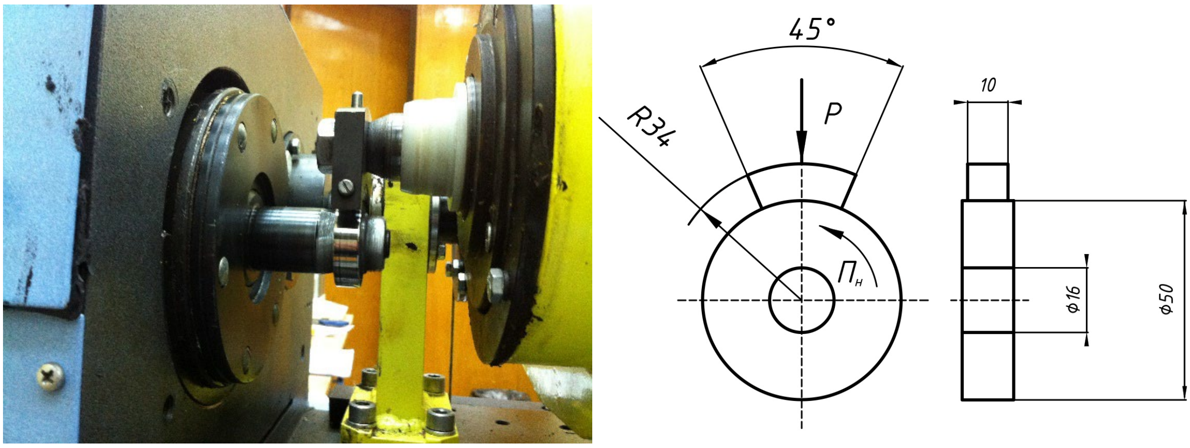
After application to the first, the second layer was subjected to heat treatment at a temperature of 250 to 400°C for one hour. The heat treatment mode did not depend on the method of applying the second layer. It was selected experimentally taking into account the best indicators for the number of through pores to the base [11]. After applying the third layer to the second one, its heat treatment was carried out in the temperature range from 300 to 450°C for one hour. To study antifriction properties of the third layer, depending on the temperature of heat treatment, a model test of several samples obtained at different temperatures was carried out.

The determination of friction characteristics of the third layer was carried out according to the "disk-pad" scheme. The coating was applied to the "pad" sample. The general view and coupling scheme of the samples are shown in Figure 2.

[1] *Paints and varnishes. Cross-cut test.* ISO 2409:2020. https://www.iso.org/standard/76041.html
[2] GOST 9.302-88. *Unified system of corrosion and ageing protection. Metal and non-metal inorganic coatings. Control methods.* URL: https://gostrf.com/normadata/1/4294850/4294850372.pdf (In Russ.).

When assigning the load for the model experiment, it was assumed that the most common type of rolling stock were high sided wagons of various modifications with an average load capacity of about 70 tons and a mass of 23 tons. Taking into account the fact that each support unit accounted for half of the total weight, and the diameter of the center pivot and the diameter of the pin hole were 302 and 54 mm, respectively, the actual contact pressures were obtained, which amounted to 6.7 MPa.

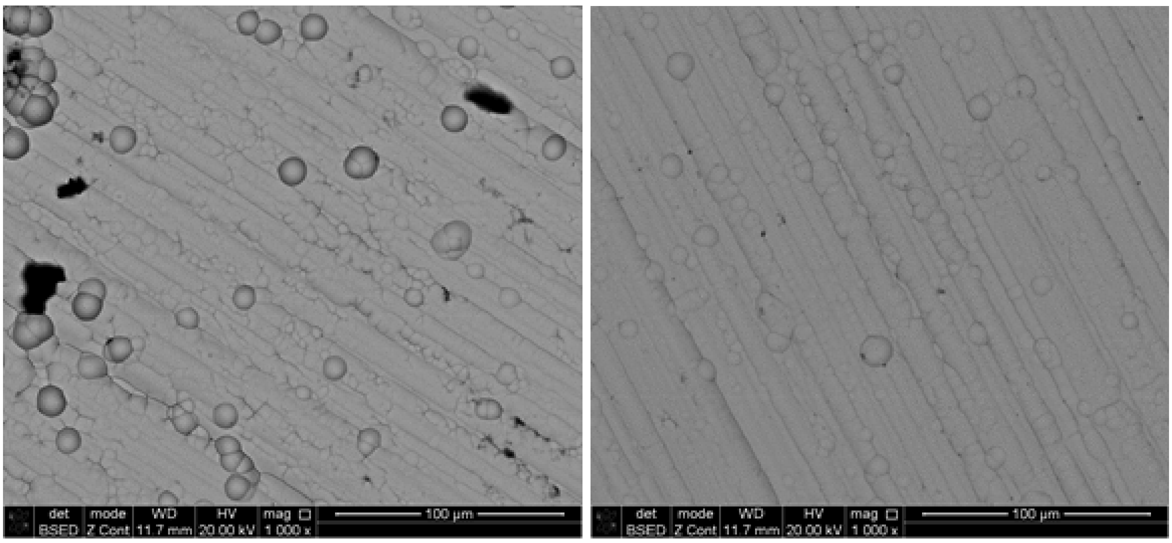
The speed of relative sliding of surfaces in the pivot assembly is determined by the radius of the curve and its current speed, set by the driver depending on the traffic conditions. Since in practice the sliding speed had small values, the minimum possible rotational speed of the shaft of the lower sample, 50 min^{-1}, was adopted for a comparative study between the samples.



a) *b*)

Fig. 2. Samples of "disk-pad": *a* — general view; *b* — coupling scheme

Results. During the study, it was found that the first layer was best obtained by using chemical deposition at a rate of up to 40 microns/h. A significant influence on the thickness and quality of the resulting coating was by the temperature of the solution and the concentration of the components. Based on the obtained adhesion measurement results, it was found that the heat treatment of the first layer was best at a temperature of 400°C for one hour. At this temperature, the Ni phase and wear-resistant Ni_3P were formed [14, 15]. Micrographs of the layer are shown in Figure 3, the element analysis in Tables 1 and 2, and the distribution of elements in the first layer is shown in Figure 4.



a) *b*)

Fig. 3. Micrographs of the first layer:

a — before heat treatment; *b* — after treatment for one hour at a temperature of 400°C

Table 1

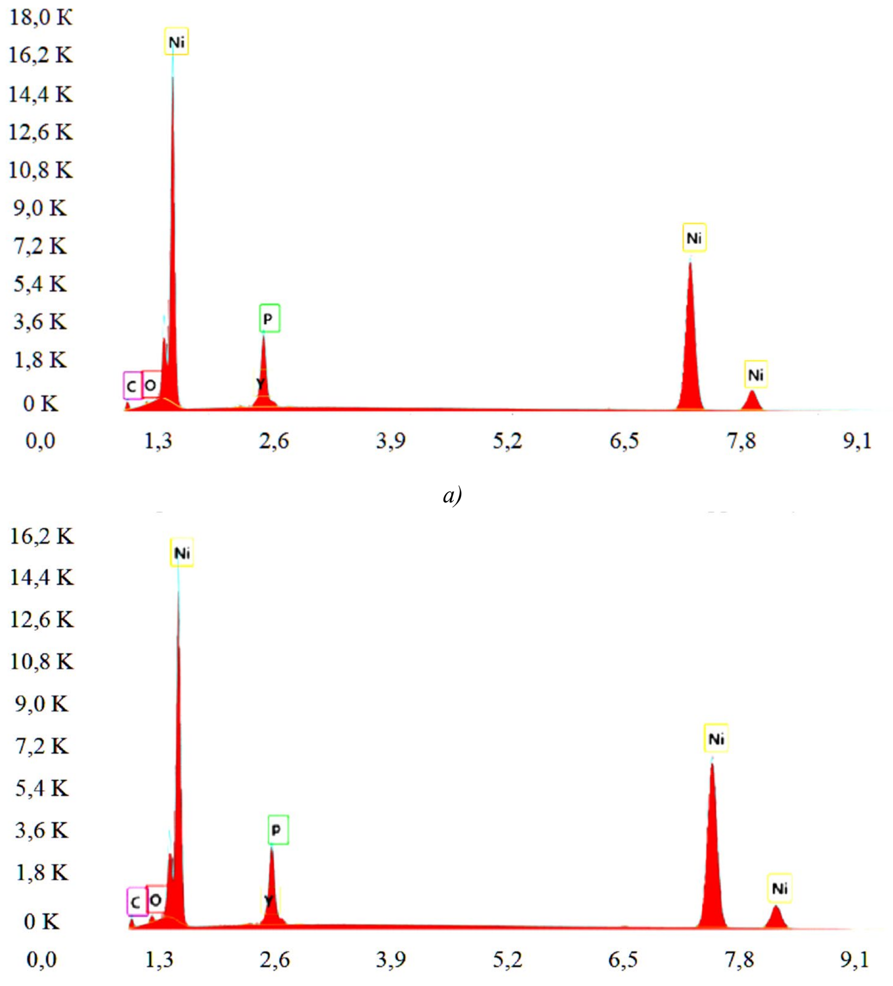
Elemental analysis of the first layer before heat treatment

Element	Weight %	MDL	Atomic %	Error %
C K	8.3	0.56	28.5	14.1
O K	0.6	0.22	1.6	23.5
P K	9.3	0.12	12.5	7.0
Ni K	79.9	0.41	56.4	2.2
Y K	2.1	0.22	1.0	10.7

Table 2

Elemental analysis of the first layer after heat treatment

Element	Weight %	MDL	Atomic %	Error %
C K	7.6	0.52	26.5	14.2
O K	1.4	0.19	3.6	13.5
P K	8.9	0.14	12.0	7.0
Ni K	80.1	0.33	57.0	2.2
Y K	2.1	0.20	1.0	10.7



b)

Fig. 4. Distribution of elements in the first layer:

a — before heat treatment; *b* — after treatment for one hour at a temperature of 400°C

Figure 5 shows a micrograph of the second layer, and Figure 6 shows the dependence of the change in the thickness of the second layer on the temperature of heat treatment and the method of coating. According to the test results, it was found that at a heat treatment temperature of 350°C for one hour, the lowest coefficient of friction for this coating was 0.07. This was significantly less in comparison with the initial coefficient of friction of 0.10–0.12 during normal operation of the unit and up to 0.18 when the lubricant was squeezed out. Table 3 provides the data on the study of antifriction properties of the third layer, depending on the temperature of its heat treatment. The proposed coating provided a reduction in the coefficient of friction by almost half, compared with the original node, even with dry friction.

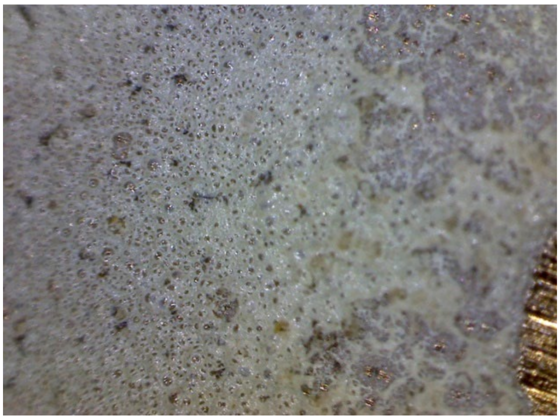


Fig. 5. Micrographs of the second layer, ×200

Table 3

Influence of the temperature of heat treatment of samples on their antifriction properties

Heat treatment temperature , °C	300	350	400	450
Coefficient of friction	0.09	0.07	0.09	0.12

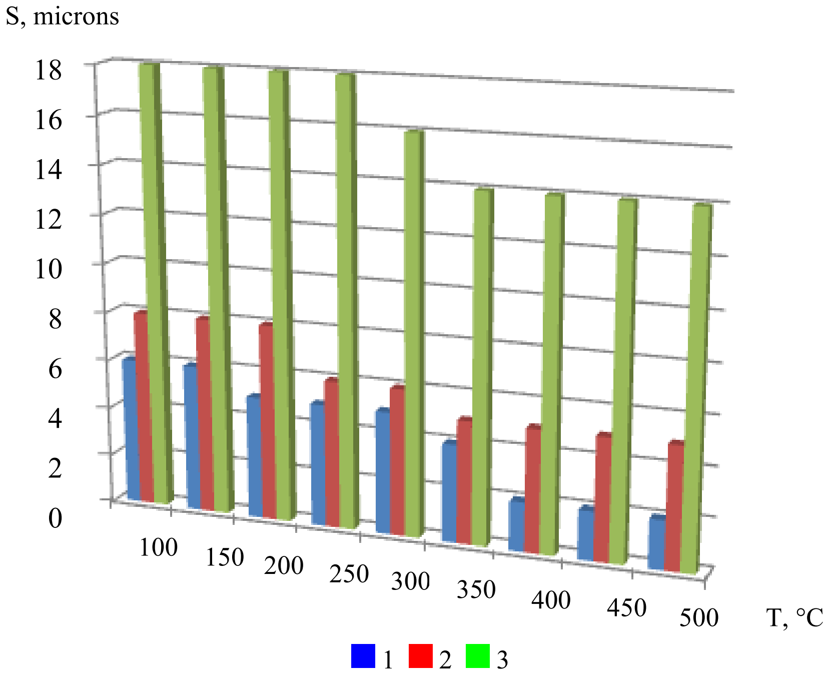
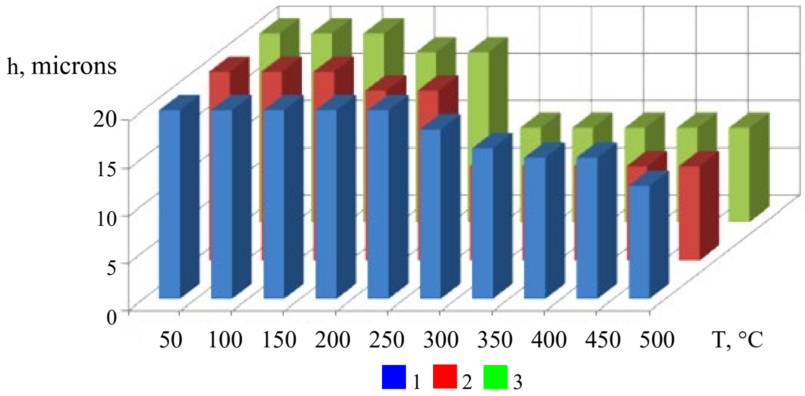


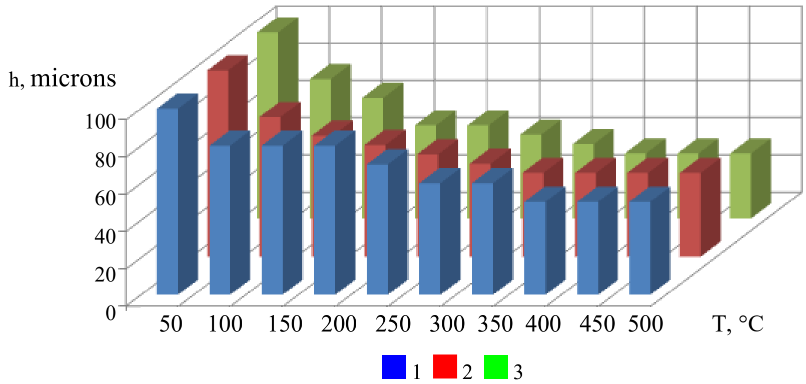
Fig. 6. Change in thickness of the second layer obtained depending on the temperature of heat treatment and the method of coating: 1 — spraying method; 2 — dipping method; 3 — spreading method

The dependence of the third layer thickness on the temperature and duration of heat treatment is shown in Figure 7.

Figure 8 shows a micrograph, and Figure 9 shows an elemental analysis of the third layer obtained at a heat treatment temperature of 350°C for one hour.



a)



b)

Fig. 7. Change in the third layer thickness at different combinations of temperature and heat treatment time:
1 — 60 min.; 2 — 120 min.; 3 — 180 min.;
a — coating is obtained by spraying; *b* — coating is obtained by spreading

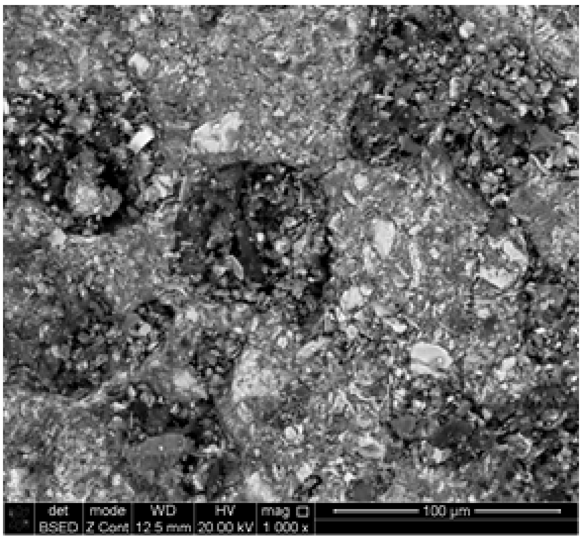


Fig. 8. Micrographs of the third layer

When measuring the adhesion of the third layer, depending on its thickness (Fig. 10), it was found that the best values of the results were obtained with a coating thickness of no more than 20 microns, which was considered optimal.

Based on the results of the obtained dependencies, a recommendation was formed to achieve optimal parameters of the last antifriction layer of the composite coating (Table 4)

Table 4

Values of optimal parameters for the antifriction layer

Element	Weight %	MDL	Atomic %	Error %
O K	35.7	0.23	60.3	10.6
Ne K	0.3	0.13	0.5	24.1
Mg K	1.3	0.10	1.5	10.2
P K	17.4	0.09	15.2	4.7
S K	14.3	0.37	12.1	5.0
Fe K	1.7	0.19	0.8	8.5
Ni K	2.5	0.28	1.1	7.8
Zn K	7.1	0.33	2.9	4.9
Sr L	0.6	0.15	0.2	11.2
Mo L	17.6	0.85	5.0	5.4
Cd L	1.5	0.23	0.4	17.8

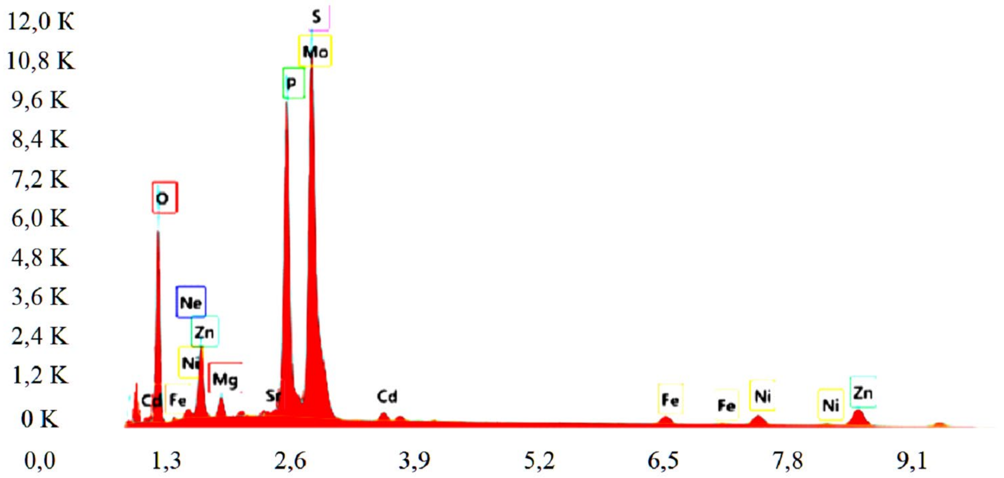


Fig. 9. Elemental analysis of the third layer

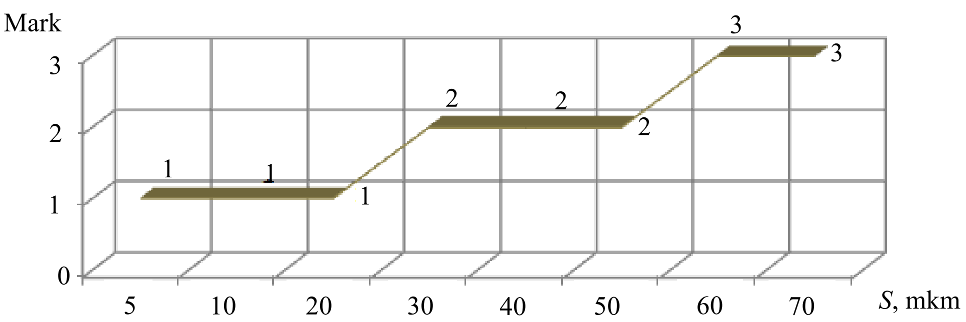


Fig. 10. Change of adhesion of the third coating layer depending on its thickness

Discussion and Conclusion. According to the results, the sample obtained at a heat treatment temperature of 350°C and exposure for one hour provides the lowest possible coefficient of friction for this coating. According to the authors, this is due to the fact that an increase in temperature above 350°C causes the appearance of oxide structures that increase the coefficient of friction. The temperature below 350°C does not allow the formation of phosphorus-containing phases that increase the antifriction properties of the third layer, which corresponds to previous studies [15].

The results obtained will increase the durability of the unit itself, reduce the wear of the ridges of wheels and rails and improve transportation safety.

The obvious advantages of the proposed solution include the facts that it:

– does not require fundamental changes in the design of the friction unit;
– is characterized by the simplicity and manufacturability of coating;
– does not require significant material costs;
– does not cancel the use of routine lubrication, but complements it;
– is universal.

The proposed solution may well be applied in any units, for example, in coupling devices of automobile rolling stock, various assemblies of lifting and transport machines, units of technological equipment, etc.

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