

# TECHNOSPHERE SAFETY

## ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ








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### Integrated Management of Fire and Occupational Risks at Enterprises

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#### Abstract

**Introduction.** Ensuring fire safety at oil and gas enterprises is a crucial aspect of occupational health and safety management system. These facilities are known to have a high concentration of flammable and explosive materials. According to statistics from the Federal Service for Environmental, Technological and Nuclear Supervision (Rostekhnadzor), approximately 38% of accidents at oil and gas facilities are related to fires and explosions. The introduction of a new method for calculating fire risk values and requirements for the occupational safety and health management system necessitates an integrated approach to fire risk management. The scientific problem is the lack of a comprehensive methodology linking fire risk assessment procedures with occupational risk management processes within a single system. The purpose of this research is to create an integrated fire risk management system that aims to enhance the effectiveness of occupational safety in oil and gas industry.

**Materials and Methods.** The research methodology was based on a systematic approach to integrating fire risk assessment procedures in accordance with Order No. 533 of the Ministry of Emergency Situations of Russia and Occupational Health and Safety Management System (OHSMS) processes. The research base consisted of data from 12 oil and gas industry facilities: four gas treatment units, three compressor stations, three oil pumping stations, and two gas distribution stations. The main facility was a gas treatment unit located in the Yamalo-Nenets Autonomous Okrug (YNAO). Initial data were collected over a period of at least three years, and a group of experts, including fire safety specialists, occupational safety engineers, and process specialists, was involved in determining the OHSMS correction factors. Expert evaluation was conducted using the Delphi method, with consistency analysis using the Kendall's coefficient of concordance ( $W = 0.82$ ). As part of the research, a mathematical model with correction factors and an integrated hazard matrix was developed. At the first stage, identification and classification of hazards were carried out in accordance with Article 9 of Federal Law No. 123-FZ “Technical Regulations on Fire Safety Requirements”, dated July 22, 2008. At the second stage, logical event trees were built and integrated metrics were calculated using JupyterNotebook (Python, Pandas, Scipy, NumPy libraries), and compared with traditional methods.

**Results.** An integrated fire risk management system was developed, which included five interrelated processes: hazard identification, risk assessment, development of management measures, monitoring and continuous improvement. A mathematical model for calculating potential fire risk was proposed, introducing the OHSMS integration coefficient, which allows for the consideration of the impact of organizational and technical occupational safety measures on fire likelihood and consequences. Within the integrated approach, 47 types of hazards were identified compared to 35 using the traditional methods, indicating more detailed risk source identification. The fire risk was reduced by 22–26% when using the integrated system compared to the baseline level.

**Discussion.** The use of an integrated approach to occupational risk management can increase its efficiency by 25–30%, due to a synergistic effect that has been confirmed by a comparative analysis of traditional and proposed risk assessment methods at oil and gas facilities. This effect is achieved through the integrated consideration of OHSMS measures, which affect the frequency and severity of fire-related incidents, while taking into account the limitations of the methodology, such as dependence on the completeness and representativeness of accident data (at least three years of observations) and focusing mainly on objects with continuous technological processes. The results obtained are consistent with international research on safety system integration, which has shown that similar approaches can improve hazard identification accuracy by 20–35% and enhance the quality of risk assessments.

**Conclusion.** The results of this study can be used to improve safety management systems at oil and gas enterprises. This includes the introduction of a mathematical model with OHSMS coefficients to reduce fire risks by 22–26%. The proposed integrated system contributes to the development of scientific foundations for risk management in industry. It opens up prospects for further research on adapting this approach to marine facilities, as well as permafrost and other extreme climates. It is recommended to use the model to optimize resource allocation in OHSMS. This should take into account the results of expert evaluations and regular revisions of parameters as more statistical data becomes available.

**Keywords:** fire safety, oil and gas industry, occupational health and safety management system, occupational risks, fire risk, hazard identification, mathematical modeling, integrated management system, industrial safety, OHSMS

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*Оригинальное эмпирическое исследование*

## Комплексное управление пожарными и профессиональными рисками на предприятиях

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### Аннотация

**Введение.** Обеспечение пожарной безопасности на предприятиях нефтегазовой отрасли является одной из самых важных задач в системе управления охраной труда, поскольку такие объекты характеризуются высокой концентрацией пожароопасных и взрывоопасных веществ. Согласно статистическим данным Федеральной службы по экологическому, технологическому и атомному надзору (Ростехнадзор), около 38 % аварий на объектах нефтегазового комплекса связано с пожарами и взрывами. Вступление в силу новой методики определения расчетных величин пожарного риска, а также требований к системе управления охраной труда обуславливает необходимость формирования интегрированного подхода к управлению пожарными рисками. Научная проблема состоит в отсутствии комплексной методологии, которая бы увязывала процедуры оценки пожарного риска с процессами управления профессиональными рисками в рамках единой системы. Целью данного исследования является разработка интегрированной системы управления пожарными рисками, ориентированной на повышение эффективности обеспечения безопасности труда на предприятиях нефтегазовой отрасли.

**Материалы и методы.** Методология исследования основана на системном подходе к интеграции процедур оценки пожарного риска согласно приказу МЧС России № 533 с процессами управления охраной труда (СУОТ). Базу исследования составили данные с 12 объектов нефтегазовой отрасли: четыре установки подготовки газа, три компрессорные станции, три нефтеперекачивающие станции и две газораспределительные станции. Основным объектом — установка подготовки газа в Ямало-Ненецком автономном округе (ЯНАО). Исходными данными служили материалы по авариям за период не менее трех лет. Для определения поправочных коэффициентов СУОТ привлечена группа экспертов: специалисты по пожарной безопасности, инженеры по охране труда и технологи. Экспертная оценка проводилась методом Дельфи с анализом согласованности по коэффициенту конкордации Кендалла ( $W = 0,82$ ). В рамках исследования разрабатывались математическая модель с по-

правочными коэффициентами и интегрированная матрица опасностей. На первом этапе были проведены идентификация и классификация опасностей согласно ст. 9 Федерального закона № 123-ФЗ от 22.07.2008 «Технический регламент о требованиях пожарной безопасности». На втором этапе построены логические деревья событий, расчет интегрированных показателей с использованием Jupyter Notebook (Python, библиотеки Pandas, Scipy, NumPy) и сопоставление с традиционными методиками.

**Результаты исследования.** Разработана интегрированная система управления пожарными рисками, включающая в себя пять взаимосвязанных процессов: идентификация опасностей, оценка риска, разработка мер управления, мониторинг и постоянное улучшение. Предложена математическая модель расчета потенциального пожарного риска с введением коэффициента интеграции СУОТ, который позволяет учесть влияние организационных и технических мер охраны труда на вероятность и последствия пожаров. В рамках интегрированного подхода выявлено 47 видов опасностей против 35 при использовании традиционной методики, что свидетельствует о более детализированной идентификации источников риска. Установлено снижение пожарного риска на 22–26 % при применении интегрированной системы, по сравнению с базовым уровнем.

**Обсуждение.** Применение интегрированного подхода обеспечивает повышение эффективности управления профессиональными рисками на 25–30 % за счет выраженного синергетического эффекта, подтвержденного сравнительным анализом традиционных и предлагаемых методов оценки рисков на нефтегазовых объектах. Указанный эффект формируется благодаря комплексному учету мероприятий СУОТ, влияющих на частоту возникновения и тяжесть последствий пожароопасных сценариев, с одновременным учетом ограничений применения методики, таких как зависимость от полноты и репрезентативности данных по авариям (не менее трех лет наблюдений) и ориентация преимущественно на объекты с непрерывными технологическими процессами. Полученные результаты согласуются с международными исследованиями по интеграции систем безопасности, где аналогичные подходы демонстрируют повышение точности идентификации опасностей на 20–35 % и улучшение качества последующей оценки рисков.

**Заключение.** Результаты исследования могут быть использованы для совершенствования систем управления безопасностью на предприятиях нефтегазовой отрасли, включая внедрение разработанной математической модели с коэффициентами СУОТ для снижения пожарных рисков на 22–26 %. Предложенная интегрированная система вносит вклад в развитие научных основ управления рисками в промышленности, открывая перспективы дальнейших исследований по адаптации данного подхода к морским объектам, а также к условиям вечной мерзлоты и других экстремальных природно-климатических зон. Рекомендуется применение модели для оптимизации распределения ресурсов в СУОТ с учетом результатов экспертной валидации и регулярного пересмотра параметров по мере накопления статистических данных.

**Ключевые слова:** пожарная безопасность, нефтегазовая отрасль, система управления охраной труда, профессиональные риски, пожарный риск, идентификация опасностей, математическое моделирование, интегрированная система управления, производственная безопасность, СУОТ

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**Introduction.** Ensuring fire safety at oil and gas industry enterprises is an important task, especially in light of current global trends towards occupational safety and health. Many countries are adopting increasingly strict norms and standards for environmental protection and worker safety, which presents additional challenges for the oil and gas sector. The absence of adequate fire safety measures can lead not only to catastrophic consequences for the health of employees, but also to significant financial losses, including compensation for victims, costs of facility restoration, and fines for legal infringements. Ignoring fire safety issues can cause devastating environmental consequences with massive leaks of hazardous substances. This, in turn, can lead to a negative perception of the industry as a whole. Thus, the urgency of developing and implementing effective fire risk management systems in the oil and gas industry is becoming indisputable, and the urgent need for an integrated approach to solving this problem in the context of global change requires immediate action. An analysis of statistical data on oil and gas industry facilities for the period 2019–2023 reveals that, despite the ongoing safety measures, significant losses from fires and explosions continue to be reported. The implementation of a new methodology for calculating fire risk values and requirements for occupational safety and health management necessitates an integrated approach to fire risk management. However, so far, no comprehensive methodology has been developed to link fire risk assessment procedures with occupational risk management processes within a single system.

According to statistics from Rostekhnadzor, between 2019 and 2023, approximately 38% of accidents at oil and gas facilities involved fires and explosions. This emphasizes the urgency of developing effective fire risk management systems. Figure 1 shows data on emergencies in the oil and gas industry for 2019–2023. Figure 2 shows the number of accidents at oil and gas production facilities over the same period.

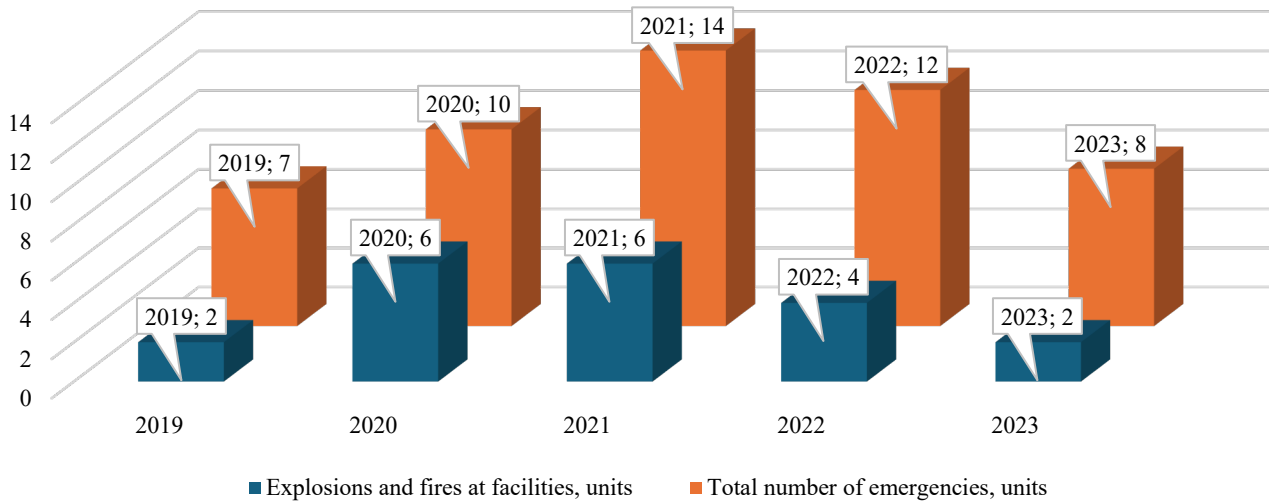


Fig. 1. Number of emergencies at oil and gas production facilities in 2019–2023

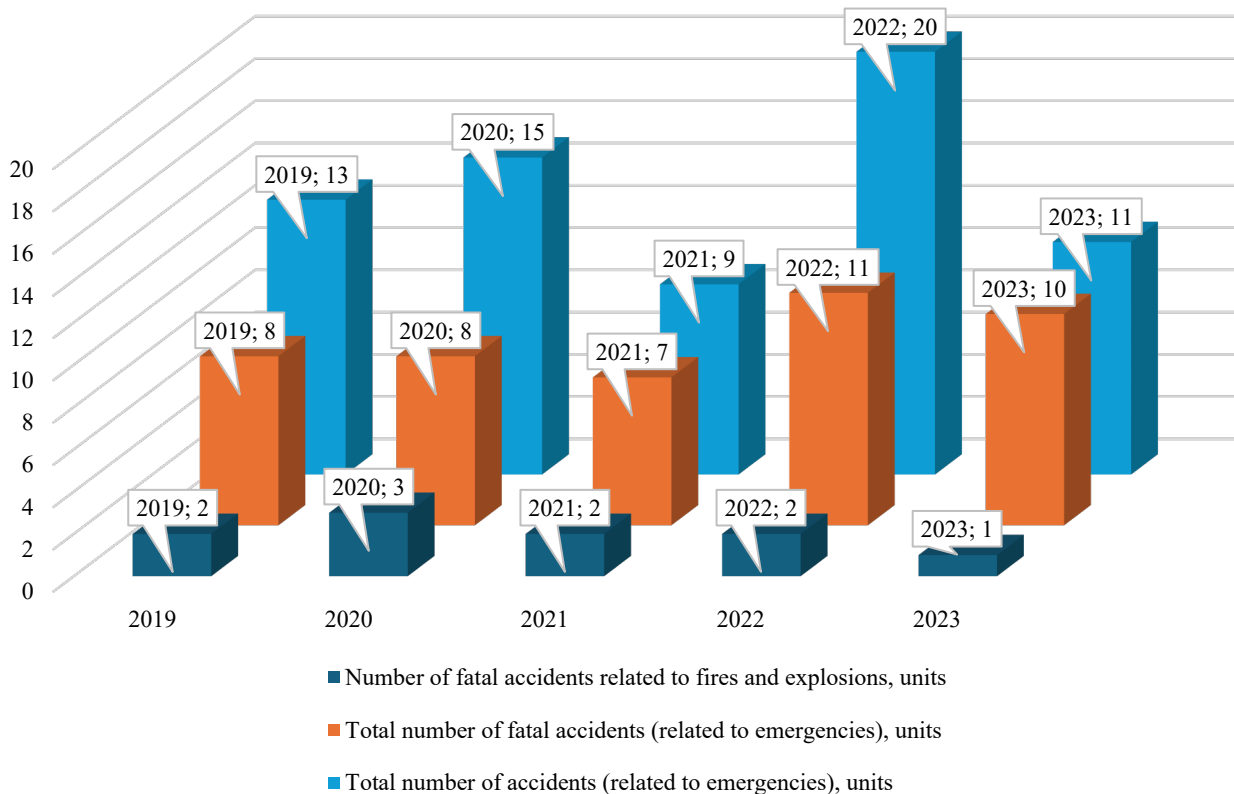


Fig. 2. Number of accidents at oil and gas production facilities in 2019–2023

The graphs show the dynamics of accidents and related consequences at oil and gas industry facilities in 2019–2023. During this period, the share of emergencies among all incidents varied in the range from 25 to 60%, with an average of 38%. The minimum number of emergencies was recorded in 2023, which indicated the effectiveness of the measures taken to manage industrial and fire safety. Similarly, the accident rate decreased from 25% in 2019 to 10% in 2023, and the five-year average was 23%. The average proportion of accidents related to fires and explosions remained at about 24%, demonstrating a steady downward trend.

Fatal accidents related to fires at the facilities under consideration remained at a relatively low level, which confirmed the effectiveness of integrated industrial and fire safety management systems, as well as ongoing preventive measures [1]. The identified trends emphasized the need for further improvement of approaches to ensuring integrated safety at oil and gas industry enterprises and the urgency of continuing work to reduce risk levels, frequency of severe and group incidents and scale of their consequences [2].

The new methodology for determining calculated fire risk values at production facilities, which entered into force on January 1, 2025 (EMERCOM of Russia Order No. 533 dated June 26, 2024)<sup>1</sup> and the current Approximate Regulation on the Occupational Health and Safety Management System (Ministry of Labor of Russia Order No. 776n dated October 29, 2021)<sup>2</sup> require the development of an integrated approach to fire risk management within the framework of the general occupational health and safety management system. The new methodology of the Russian Ministry of Emergency Situations maintains a comprehensive list of fire hazards as defined in Article 9 of Federal Law No. 123-FZ, while also clarifying criteria for human injuries and approaches to simulating fire scenarios and assessing associated risks. Main changes relate to details of calculation procedures and requirements for analyzing initial events and justifying initial data, rather than adding new hazardous factors. At the same time, the requirements of the occupational health and safety management system include regular identification of hazards and assessment of occupational risks. This forms the methodological basis for integrating fire risk assessment procedures into the overall occupational health and safety management system [3].

An analysis of modern scientific research reveals that in most studies the issues of fire safety and occupational safety are considered separately, without sufficient elaboration of their relationship [4]. However, the specific nature of the oil and gas industry necessitates the implementation of an integrated approach [5], which focuses on recognizing the mutual influence of different types of occupational and fire hazards, as well as their combined effect on the safety of production [6].

The aim of this research is to develop an integrated fire risk management system based on the requirements of the current methodology of the Russian Ministry of Emergency Situations, as well as the principles of occupational safety management systems, in order to improve the efficiency of occupational safety at oil and gas industry enterprises and reduce the probability of dangerous events.

**Materials and Methods.** The research methodology was based on a systematic approach to integrating fire risk assessment procedures in accordance with Order of the Ministry of Emergency Situations of Russia No. 533 and occupational risk management processes within the OHSMS in accordance with Order of the Ministry of Labor of Russia No. 776n. The research included the development of an integrated hazard matrix that linked primary and associated fire hazards (according to Federal Law No. 123-FZ) with occupational risks for various categories of personnel. Experts in fire safety and labor protection participated in validating the methodology. Methods of expert assessment and statistical analysis were used.

The research was conducted based on data from 12 oil and gas industry facilities located in the Yamalo-Nenets Autonomous Okrug and part of a large joint-stock oil and gas production company. To ensure the representativeness of the sample, we used the following criteria: the presence of a certified occupational health and safety management system in accordance with GOST R ISO 45001; the availability of information on industrial accidents for at least the last five years; the presence of data on inspections by regulatory bodies in the field of industrial safety and labor protection; and the variety of technological processes and equipment used. The sample included four gas treatment units with a capacity of 15 to 45 million m<sup>3</sup>/day and an operating pressure of up to 25 MPa, three step compression compressor stations with a capacity of 40–80 million m<sup>3</sup>/day with a total capacity of 12–32 MW and an injection pressure of up to 10 MPa, three oil pumping stations (oil pipeline) with a capacity of 8–25 million tons per year and with a supply pressure of up to 6 MPa, two gas distribution stations with a reduction pressure of 2.5 to 1.2 MPa and a capacity of up to 3.5 million m<sup>3</sup>/day. The following data was collected and analyzed for each facility: acts and protocols of inspections of supervisory authorities in the field of industrial safety and labor protection for 2018–2023, registers of industrial incidents, including cases of pipeline integrity violations, hydrocarbon leaks, equipment failures and personnel injuries, results of hazard analysis conducted by the company (HAZOP, analysis of the types and consequences of failures), equipment parameters from technical documentation and plant data sheets, data on fire scenarios, calculated using models in software packages (PHAST, ALOHA or equivalent), information on occupational safety and fire safety measures, incident reports and disability sheets related to occupational risks. The database on violations of fire and industrial safety requirements was compiled on the basis of open registers of supervisory authorities and internal registers of the company.

<sup>1</sup> *On Approval of the Methodology for Determining Calculated Fire Risk Values at Production Facilities.* Order of the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters No. 533 dated 26.06.2024. (In Russ.) URL: <http://publication.pravo.gov.ru/document/0001202409030008> (accessed: 18.12.2025).

<sup>2</sup> *On Approval of the Approximate Regulations on the Occupational Health and Safety Management System.* (In Russ.) URL: <https://normativ.kontur.ru/document?moduleId=1&documentId=409457> (accessed: 28.10.2025)

The proposed integrated system included the following interrelated processes. The first process was the identification of fire hazards as part of the overall process of identifying occupational risks according to OHSMS. The second was the assessment of fire risk using Methodology of the Russian Ministry of Emergency Situations No. 533. The third was the development of integrated risk management measures. The fourth was the monitoring and control of the effectiveness of the measures taken. The fifth was the continuous improvement of the risk management system [7].

Mathematical model of integrated risk assessment contained a calculation of the potential fire risk within the integrated system and was determined by the formula:

$$P_{int}(a) = K_{OHSMS} \cdot \sum_{j=1}^J Q_j \cdot Q_{\delta ij}(a), \quad (1)$$

where  $K_{OHSMS}$  — coefficient of integration with OHSMS, which takes into account the effectiveness of the occupational safety management system;  $J$  — number of fire scenarios;  $Q_j$  — frequency of implementation of the  $j$ -th fire scenario, year<sup>-1</sup>;  $Q_{\delta ij}(a)$  — conditional probability of human injury during implementation the  $j$ -th scenario.

Coefficient of integration with OHSMS is determined by the formula:

$$K_{OHSMS} = K_{ident} \cdot K_{train} \cdot K_{cont} \cdot K_{impr}, \quad (2)$$

where  $K_{ident}$  — coefficient of effectiveness of hazard identification (0.8–1.2);  $K_{train}$  — coefficient of effectiveness of personnel training (0.7–1.1);  $K_{cont}$  — coefficient of effectiveness of control (0.8–1.3);  $K_{impr}$  — coefficient of continuous improvement (0.9–1.1).

To determine the values of the coefficients and validate the model, a group of 15 experts was involved: five fire safety specialists with work experience from 8 to 25 years, five occupational safety engineers with experience from 6 to 20 years, and five process specialists with experience from 10 to 30 years. The criteria for the selection of experts were higher professional education, at least five years of work experience at oil and gas facilities, certificates in the field of industrial safety, as well as the absence of a conflict of interest with the facilities. Expert evaluation of coefficients  $K_{ident}$ ,  $K_{train}$ ,  $K_{cont}$ ,  $K_{impr}$  was conducted using the Delphi method in three rounds in the form of an anonymous questionnaire: in the first round, experts gave individual estimates (within predefined acceptable values); in the second round they were provided with an aggregative summary of the group (median and interquartile range for each coefficient) with a suggestion to clarify the answers; in the third round, the confirmation of the agreed values was performed. The consistency was controlled by the Kendall's concordance coefficient ( $W = 0.82$ ). The final values of the coefficients were determined as the medians of expert estimates, and the interval values (ranges) were set by the boundaries of the interquartile range (25th and 75th percentiles), followed by rounding to values convenient for practical use.

The values of the coefficients in formula (2) were determined based on an expert assessment using the Delphi method and statistical analysis of Kendall's consistency. The ranges were selected taking into account data from similar studies [6–10]:  $K_{ident}$  reflected the variability of hazard detection depending on the completeness of databases;  $K_{train}$  — impact of staff training on reducing the frequency of incidents;  $K_{cont}$  — effectiveness of monitoring equipment based on historical accident data;  $K_{impr}$  — contribution of iterative improvements in OHSMS to long-term risk reduction.

The Kendall's concordance coefficient ( $W = 0.82$ ) and ANOVA analysis were used to determine the significance of differences between groups. Pearson correlation analysis was used to identify relationships between parameters as statistical processing methods. The calculations were performed in the Jupyter Notebook development environment using Python and the Matplotlib, Pandas, Scipy, and NumPy libraries.

Table 1 shows an integrated hazard matrix developed based on the analysis of the requirements of Order of the Ministry of Labor of Russia No. 776n (Occupational Risk Management System) and Methodology of the Ministry of Emergency Situations of Russia No. 533 (Fire Risk Assessment), taking into account the classification of fires according to Art. 8 of Federal Law No. 123-FZ (classes A–F) and an exhaustive list of fire hazards according to Art. 9 (primary factors: flames and sparks, heat flow, elevated temperature, toxic products, low oxygen concentration, reduced visibility; collateral: fragments, radioactive/toxic substances, high voltage, explosion factors, exposure to extinguishing agents). The matrix provides a comprehensive identification of hazards, linking them with occupational risks for oil and gas facilities, where classes B (flammable liquids), C (gases) and E (live electrical installations) prevail.

When creating a matrix for each hazard, we recorded the corresponding fire hazard factor (primary or collateral), the association with occupational risk, the criteria for assigning the risk level set through the probability range of the scenario (year<sup>-1</sup>), and the expected severity of the consequences for personnel (such as burns, poisoning, or electrical injury).

The matrix was used to qualitatively rank hazards and select priority management measures, as well as an input for logical event trees. At the same time, the values of correction coefficients  $K_{ident}$ ,  $K_{train}$ ,  $K_{cont}$ ,  $K_{impr}$  were determined separately according to the expert procedure (Delphi method) and then substituted into formula (2).

Table 1

Integrated hazard matrix at oil and gas facilities

Hazard group (Order No. 776n)	Hazard (an example for the oil and gas industry)	Hazard factor (Art. 9 123-FZ)	Hazard type	Connection with occupational risk (Order No.776h)	Risk level	Assignment concept
Mechanical	Depressurization of gas pipelines	Fragments from equipment destruction	Collateral	Risk of injury during maintenance	High	Probability > 0.01 year <sup>-1</sup> + >50 staff
Thermal	Ignition of hydrocarbon vapors	Flames and sparks, heat flow	Primary	Burns and heat injuries	High	Probability > 0.001 year <sup>-1</sup> + severe burns
Chemical	Release of toxic gases in case of fire	Increased concentration of toxic products	Primary	Poisoning/Occup. disease	Average	Probability —0.0001–0.001 year <sup>-1</sup> + toxicity zone
Explosion and fire-hazardous	Gas-air mixture explosion	Explosion hazards	Collateral	Shock wave, injuries	High	Probability > 0.001 year <sup>-1</sup> + shock wave
Electric	Short circuit in electrical installations	Electric shock, electric arc injury	Collateral	Electric shock	Average	Probability —0.0001–0.001 year <sup>-1</sup> + electrical injury
Toxicological	Smoke from the burning of insulation	Reduced visibility, reduced O <sub>2</sub> concentration	Primary	Suffocation, disorientation	High	Probability > 0.01 year <sup>-1</sup> + suffocation/disorientation
Physical	Increased temperature in the compressor room	Increased temperature	Primary	Heat stress	Average	Probability —0,0001–0.001 year <sup>-1</sup> + heat stress

The expanded matrix took into account the classification characteristics of fire hazards according to Federal Law No. 123-FZ, providing full coverage of primary and related manifestations. Integration with Order No. 776n made it possible to systematically identify hazards in the OHSMS, minimizing occupational risks (injuries, diseases) at facilities with a high fire risk. Validation of the integrated hazard matrix was performed by an expert group as part of an expert procedure (Delphi method): The experts assessed 1) the completeness of coverage of fire hazards according to Art. 9 of Federal Law No. 123 FZ (the presence of primary and collateral factors), 2) the correctness of assigning hazards to groups by Order of the Ministry of Labor of the Russian Federation No. 776n, 3) the validity of the “hazard — occupational risk” relationship for categories of personnel, 4) the unambiguity of the wording of the matrix lines, and 5) the validity of assigning the risk level according to the criteria given in the corresponding column “Assignment criteria”. Based on the results of the analysis of the experts' comments, the formulations of individual lines and criteria for assigning risk levels were clarified, and the final version of the matrix was recognized as applicable to oil and gas facilities within the framework of the proposed approach.

The logical event trees were constructed taking into account the impact of the occupational health and safety management system on the development of fire-hazardous situations. The integrated risks were calculated using correction factors reflecting the effectiveness of the occupational health and safety management system.

To account for the impact of OHSMS on the frequency of fire-hazardous situations, a modified formula was used:

$$Q_{j,mod} = Q_{j,base} \cdot \prod_{k=1}^n (1 - E_k \cdot P_k), \tag{3}$$

where  $Q_{j,base}$  — base frequency of the  $j$ -th scenario;  $E_k$  — effectiveness of the  $k$ -th OHSMS event;  $P_k$  — probability of triggering  $k$ -th event;  $n$  — number of applicable OHSMS events [11].

To quantify the potential fire risk on the territory of the gas treatment facility, five control points (A–E) were selected, characterizing various zones of potential exposure to fire hazards. Point A corresponded to the compressor equipment area (high pressure and high concentration of process equipment). Point B corresponded to the gas drying unit area. Point C corresponded to the gas-handling equipment area. Point D corresponded to the administration and amenity area. Point E corresponded to the border of the sanitary protection zone of the facility.

The initial data for the development of the integrated system were collected from 12 oil and gas industry facilities that were included in the sample. At the same time, the gas treatment plant in the Yamalo-Nenets Autonomous District was used as the basis for detailed testing and calibration of the calculation procedures. This facility included various types of technological equipment for the full cycle of natural gas drying and purification. Based on the results of data processing from these facilities, a database of violations of fire and industrial safety requirements was created [12].

**Results.** The integrated approach identified 47 types of hazards, of which 23 related to fire hazards, 18 — to general occupational hazards, and 6 — to combined hazards requiring special consideration (Table 2).

Table 2

Results of integrated hazard identification

Hazard type	Number of identified hazards	Critical risk level	Required management measures
Fire	23	8	Technical and organizational
Occupational	18	5	Mostly organizational
Combined	6	6	Comprehensive measures

Table 3 provides the results of comparing different approaches to risk management.

Table 3

Comparison of the effectiveness of different approaches to risk management

Indicator	Traditional approach	Integrated approach
Number of identified hazards	35	47
Accuracy of risk assessment	0.75	0.92

The results of calculating the potential fire risk based on control points (A–E) are presented in Figure 3. The analysis of the potential fire risk values calculated using the traditional method and the proposed integrated approach showed that the integrated method provided a more conservative assessment of risk at all control points in the facility. The largest difference was observed at point A, where the integrated assessment exceeded the traditional one by 17%. This was due to additional factors that affected the development of fire-hazardous situations. This difference in estimates confirmed the need for an integrated approach to obtain a more accurate assessment of fire risks at oil and gas facilities.

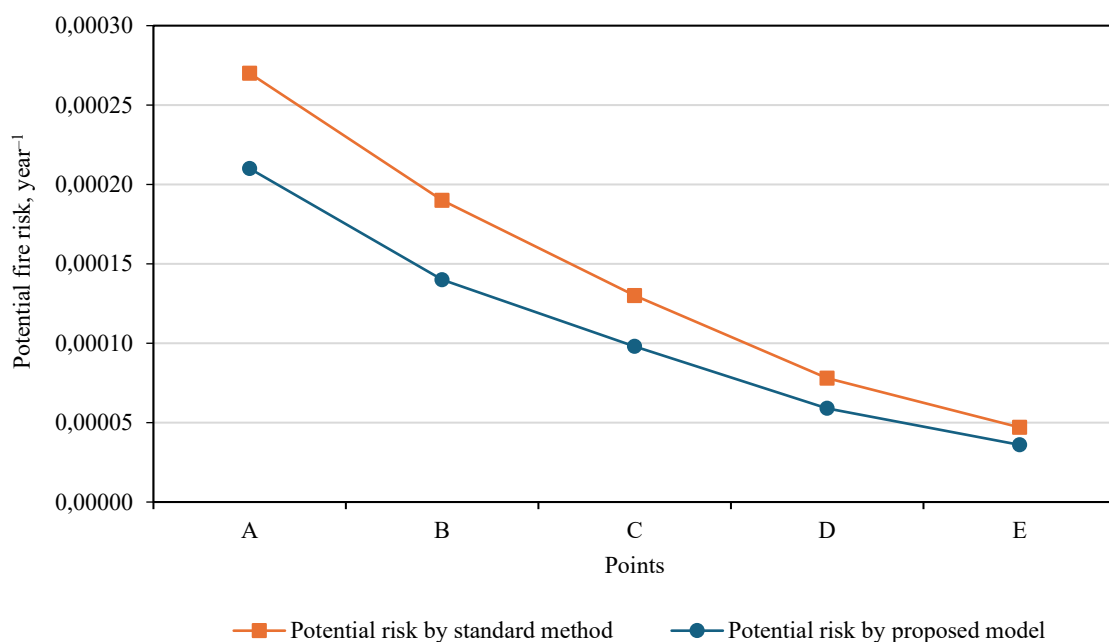


Fig. 3. Comparison of potential fire risk by control points

Table 4 presents the calculation results for potential fire risk, considering integration with the OHSMS.

Table 4

Values of integrated potential fire risk

Point	Traditional method, year <sup>-1</sup>	Integrated approach, year <sup>-1</sup>	Risk reduction, %
A	$2.7 \times 10^{-4}$	$2.1 \times 10^{-4}$	22
B	$1.9 \times 10^{-4}$	$1.4 \times 10^{-4}$	26
C	$1.3 \times 10^{-4}$	$9.8 \times 10^{-5}$	5
D	$7.8 \times 10^{-5}$	$5.9 \times 10^{-5}$	24
E	$4.7 \times 10^{-5}$	$3.6 \times 10^{-5}$	23

A comparative analysis of the results confirmed that the integrated approach reduced the estimated values of potential fire risk at all control points (A–E), compared to the traditional method. The greatest decrease was observed at point B (26%), while the smallest decrease was at point C (5%), reflecting differences in the technological loads and conditions that contribute to the formation of fire hazardous scenarios in the respective areas of the facility.

The comparative analysis of individual fire risk for different categories of workers is presented in Figure 4. The graph clearly illustrates the differences in risk levels according to the traditional methodology and the proposed integrated model for all categories of personnel. The highest risk values were typical for operators of technological installations, due to their direct contact with fire-hazardous equipment and substances. The integrated model showed an increase in estimated risk of 22–29% for all categories of employees, compared to the standard methodology. This difference was especially important for operators and maintenance staff, since their risk was approaching the maximum allowable value of  $10^{-4}$  year<sup>-1</sup>, established for production facilities with specific functioning of technological processes in accordance with Order of the Ministry of Emergency Situations of Russia No. 533.

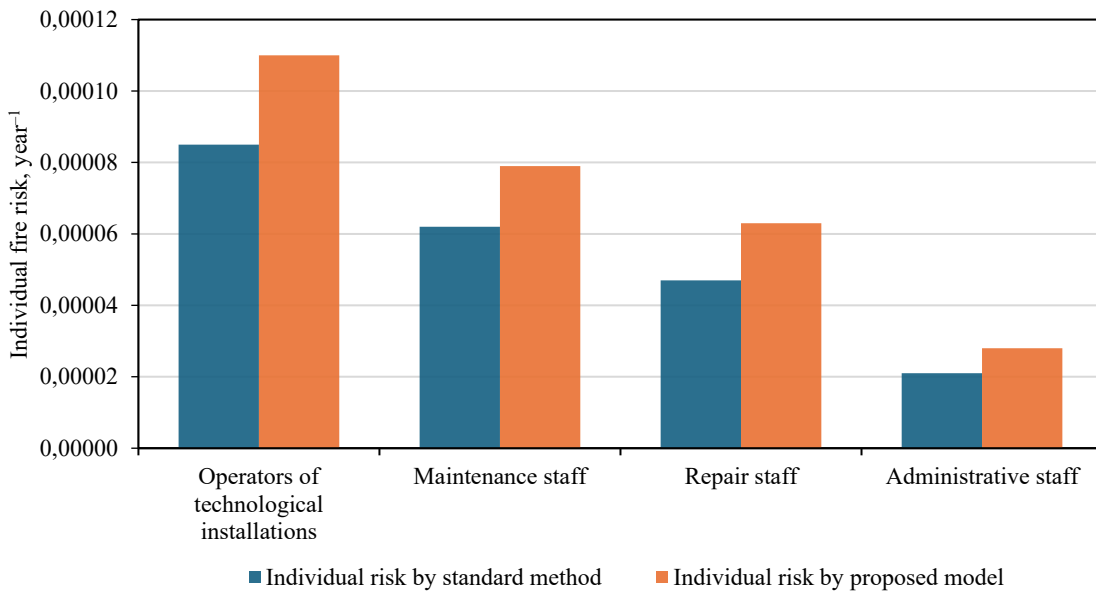


Fig. 4. Individual fire risk by employee category

To assess the contribution of various OHSMS elements to reducing fire risk, an analysis of the effectiveness of individual measures was conducted. The study found that monitoring the condition of equipment had the greatest impact on reducing fire risk. This was due to the importance of maintaining the equipment's technical condition in order to prevent depressurization and leaks. Training for staff was the second most effective measure (with an 18% reduction in fire risk), and it had the best efficiency-to-cost ratio. By analyzing the efficiency and cost ratios, it was possible to optimize resource allocation for OHSMS implementation.

The dynamics of changes in individual fire risk during the phased implementation of the integrated system is shown in Figure 5. The graph demonstrates a gradual reduction in risk for all categories of employees as each OHSMS element was implemented. The most significant decrease in risk occurred at the stage when the control system was implemented, confirming the critical importance of monitoring equipment condition and compliance with safety regulations. Operators of technological installations, who were most exposed to risk, showed the largest absolute decrease in risk — from  $1.1 \times 10^{-4}$  to  $6.3 \times 10^{-5}$  year<sup>-1</sup>. The full integration of all OHSMS elements ensured the achievement of targeted risk levels for all employee categories.

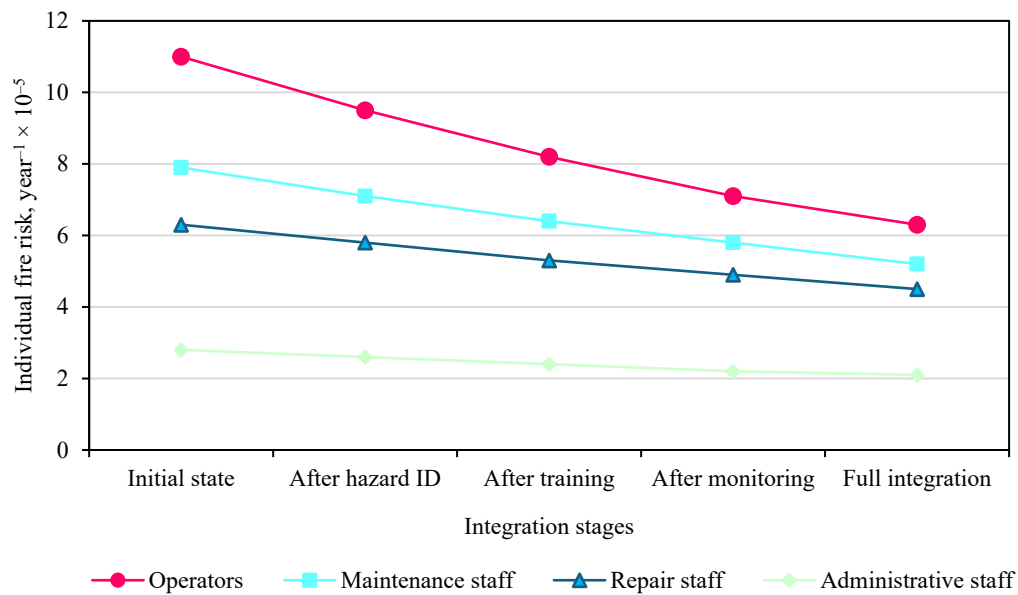


Fig. 5. Dynamics of reduction of individual fire risk when implementing an integrated system

**Discussion.** The integrated probabilistic statistical risk assessment model, which incorporates the elements of the occupational health and safety management system (OHSMS), allows us to quantify the dynamics of risks during the phased implementation of measures. Its use at oil and gas industry facilities has confirmed its suitability for analyzing the impact of both technical and organizational solutions on fire and industrial safety levels. The results have shown that the initial (baseline) risk values without the effects of OHSMS elements could be significantly higher than traditionally accepted estimates due to the consideration of a large number of scenarios and failures, as well as the human factor. However, the step-by-step implementation of measures provided by the management system has ensured a noticeable reduction in both potential and individual fire risks, bringing them to acceptable targets. This emphasizes the importance of transitioning from a purely formal approach to fulfilling requirements to a more quantitative-based approach in management.

Of particular importance are the system for monitoring the technical condition of equipment, timely maintenance, and staff training. Modeling has demonstrated that these elements have the greatest effect in reducing the frequency of triggering events and erroneous actions, while being characterized by a favorable efficiency-cost ratio. Considering their influence in the integrated model makes it possible to justify priorities in planning activities and allocating resources.

Comparison with international standards has shown that the proposed methodology largely meets modern requirements in the field of industrial and occupational safety management. It can be considered a practical tool for adapting existing management systems to current regulatory requirements and increasing the transparency of decisions. The developed methodology is consistent with the requirements of GOST R ISO 45001–2020 and modern approaches to risk-based safety management. The implemented approach ensures compliance with most of the provisions of the standard than using the traditional approach. Integration with elements of HAZOP analysis improves the quality of hazard identification compared to using standard procedures.

However, the developed methodology has some limitations in its application. It is designed for facilities with continuous processes and requires a database of incidents for at least three years, as well as a specific set of technological processes to ensure the accuracy of the assumptions. The effectiveness of this approach decreases when there are fewer than 50 employees. Additionally, the methodology does not account for the unique characteristics of offshore facilities or those located in permafrost conditions, which requires careful consideration when applying the developed model to different operating environments.

According to the research results, the Federal Intellectual Property Service has registered the computer program “Program for Analyzing the State of Industrial Safety” [13], which expands the possibilities of its use at various production facilities. This includes automation of calculations and the generation of accounting documentation.

**Conclusion.** The conducted research has shown that the integration of fire risk assessment procedures in accordance with the EMERCOM of Russia Methodology No. 533 and occupational risk management processes into the occupational safety management system (Order of the Ministry of Labor of the Russian Federation No. 776n) is an effective means of improving occupational safety in the oil and gas industry. This integrated approach enables us to consider fire safety and occupational safety as components of a unified risk management framework.

An integrated hazard matrix has been developed, taking into account the classification according to Federal Law No. 123-FZ and linking it to the occupational risks of oil and gas facilities. This matrix has increased the number of identified hazards from 35 to 47, including combined hazards that require special comprehensive measures. This confirms a more comprehensive identification of risks.

A mathematical model of integrated fire risk assessment has been developed with an integration coefficient with the OHSMS and a modified formula for the frequency of occurrence of fire-related scenarios, taking into account the effectiveness of OHSMS measures. Validation using expert estimates and statistical methods (Kendall concordance coefficient, ANOVA, correlation analysis), have shown that the coefficients are sufficiently consistent and valid.

Practical testing at oil and gas industry facilities has demonstrated an increase in the accuracy of risk assessment from 0.75 to 0.92 and a reduction in fire risk levels with the step-by-step introduction of elements of the OHSMS, especially systems for monitoring the technical condition of equipment and personnel training.

The prospects for future research include adapting the methodology for facilities with special operational modes and increased risk, expanding the list of scenarios under consideration, as well as a more detailed integration of aspects of the human factor and digitalization of monitoring: the use of online monitoring systems, intelligent diagnostics, and big data analysis.

In general, the proposed approach forms the basis for improving fire and industrial safety management practices in the oil and gas industry, ensuring more informed decision-making to reduce risks.

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