

M. Moroz<sup>1</sup>, E. Mykhailova<sup>2</sup>, V. Shavkun<sup>1</sup>

<sup>1</sup>*O. M. Beketov National University of Urban Economy in Kharkiv, Ukraine*

<sup>2</sup>*Simon Kuznets Kharkov National University of Economic*

## RELIABILITY ANALYSIS OF HIGH- RISK FACILITIES AND ASSESSMENT OF EMERGENCY CONSEQUENCES FOR THE POPULATION

*The article investigates the reliability and safety of high-risk gas transmission system facilities under modern technogenic, natural, and military threats. FMEA and FTA methods are applied to identify critical equipment failures, their causes, and consequences. Modernization, monitoring, automation, and personnel training are proposed to reduce risks and accidents.*

**Keywords:** *gas transmission system, high-risk facilities, reliability, industrial safety, risk assessment, emergency situations.*

### Introduction

Since the beginning of the full-scale armed attack on Ukraine, the population of our country has suffered enormous losses. Military actions have damaged and destroyed hundreds of institutions and enterprises across various sectors [1]. There is a significant number of high-hazard facilities (HHF) on the territory of our country – enterprises where hazardous substances are used, stored, or transported. These facilities pose a threat of emergency situations that can cause harm to people or the environment.

Such facilities include chemically hazardous enterprises, oil depots and gas storage facilities, energy facilities, explosive and fire-hazardous production sites, and transport hubs with dangerous goods, among others. In the current context, the reliability and safety of high-hazard facilities are critical components for the state as a whole, as well as for the employees of these enterprises and residents living nearby.

Reliability is a characteristic that determines a facility's ability to perform its intended functions under stable technological parameters and at an appropriate safety level for a specified period. Specifically, it implies accident-free operation, serviceability throughout the designated working time, the ability for rapid recovery, and the maintenance of a required safety level where risks to the personnel and the population are minimized.

Main gas pipelines and technological equipment, such as compressor stations, gas distribution and metering stations, underground gas storage facilities, etc., are among the high-hazard facilities. These facilities are part of the gas transportation system, which transports gas under high pressure, requiring specialized safety regulations. The operational safety of such facilities is not only of local importance regarding their locations – with

potential leaks and consequences such as fires or explosions in case of damage – but also of strategic significance for our country [2].

The strategic component concerns the assurance of energy security, specifically the transportation of natural gas for the needs of the population, industry, and the energy sector. It significantly impacts the stability of our country's economy, as the operation of numerous enterprises across various sectors of the national economy, as well as the heating of our homes, depends on a reliable gas supply. Furthermore, it is a vital part of the European energy infrastructure, and Ukraine has long served as a key transit state.

### Literature Review

The reliability and operational safety of main gas pipelines are considered in various scientific studies [3–5]. This is of great importance not only in technological and economic terms but also from the perspective of the security environment. Safety issues inevitably arise when addressing the general range of challenges due to certain technological problems within Ukraine's gas transportation industry, namely:

- the aging of infrastructure, as most main gas pipelines and compressor stations have been in operation for over 40 years, which leads to an increased risk of accidents, gas leaks, and failures of technological equipment;

- the obsolescence of control and automation systems that do not meet modern requirements for operational efficiency, safety assurance, and integration into contemporary control systems, including the lack of remote control capabilities, as well as outdated telemechanics systems that do not allow real-time monitoring of all parameters, among other limitations

– the inefficiency of energy consumption in the operation of old compressors with low efficiency, in some cases involving manual or partially automated control of operating modes, the absence of optimized gas flow distribution, as well as significant energy losses due to downtime caused by accidents and equipment failures

– the lack of modern monitoring systems employing advanced leak detection sensors, pressure and temperature control, and their integration into a unified data acquisition system in order to prevent various types of emergencies involving uncontrolled gas losses and other hazards.

Ukraine's gas transmission network and underground gas storage facilities are of crucial importance not only for the national economy but also for Europe's energy security, especially during the transitional period after 2025 [6]. This large-scale interdisciplinary study examines the efficient operation of the gas transmission network, considering organizational and technical factors as integral components of its reliable performance, and provides recommendations for the integration of Ukrainian facilities into European energy markets. The analysis is based on modelling and evaluation of scenarios for 2026–2030 and forecasts of supply volumes related to organizational and technical readiness for gas transportation.

The study by the authors in [7] is devoted to the automation of control of Ukraine's gas transmission system from the perspective of functional standards and the integration of modern solutions and measures. The processes of technological equipment control, addressing issues of information interaction among components of automated systems, and the vertical interdependence between technical processes and strategic management reveal certain areas requiring improvement and consistent transformation. In the context of operational reliability and digital transformation aimed at optimizing technological processes, a phased approach is proposed for the development of a unified operational control system based on existing automated solutions and monitoring.

Issues related to changes over time that require significant investment are considered in [8]. Insufficient investment is needed for the modernization of the gas transmission system (GTS), including the adaptation of control systems to modern European standards in organizational, technical, and safety dimensions, in accordance with the requirements of action plans reflecting modernization projects, is highlighted. This requires substantial capital investment; however, limited financial resources, an unstable economic situation, and current risks complicate the process of attracting foreign investors for the necessary financial investments.

Despite existing threats, the European energy market opens up a number of opportunities. One of the key prospects is the adoption of standards and the implementation into national legislation of the requirements set out in energy-related regulatory documents of international organizations such as the International Energy Agency, the Energy Community Secretariat, and the United Nations Economic Commission for Europe [9]. For Ukraine, from the standpoint of overall strategy and the implementation of specific programs in the energy sector, a crucial factor of stability is the reliable and continuous operation of the system, which cannot be ensured without taking existing threats into account, assessing risks to the safe operation of equipment and personnel. Therefore, determining the probability of hazardous events and evaluating their potential consequences for people, equipment, and the environment in the context of continuous gas transportation is a highly important and relevant issue.

### **Research Aim**

The aim of this article is to provide a comprehensive analysis of the reliability of gas transmission system (GTS) facilities, with an assessment of existing threats and environmental impacts. To achieve this objective, the following tasks must be addressed:

- analysis of the current state and operating features of GTS facilities, including technical characteristics and operating conditions;
- identification of the main threats to the operation of GTS facilities, including technogenic, natural, organizational, and external factors;
- assessment of hazard levels associated with the occurrence of emergencies, taking into account the probability of equipment failures and the human factor;
- study of the impact of accidents and abnormal operating modes of the GTS on the environment;
- analysis of the environmental safety of GTS facilities;
- identification of the most critical elements of the gas transmission system that require priority measures to enhance reliability and safety;
- substantiation of directions for risk reduction and minimization of negative environmental impacts;
- formulation of practical recommendations to improve the reliability and environmental safety of GTS facilities under contemporary challenges.

### **Discussion of Results**

The gas transmission system is a complex engineering and technical infrastructure comprising a wide range of diverse equipment, including main gas pipelines, compressor stations, gas distribution and gas

metering stations, communication networks and underground gas storage facilities, as well as automation systems and dispatch control of technological processes.

The current condition of a significant portion of GTS facilities is characterized by a high degree of physical and moral obsolescence of equipment, resulting from long operating periods that often exceed their design service life. Main gas pipelines operate under conditions of variable loads, exposure to corrosion processes, temperature fluctuations, and mechanical stresses, which increases the risk of failures.

The technical operating characteristics involve pressurized processes utilizing pipelines with varying throughput capacities, high-power compressor units, and automated control systems. Due to outdated technologies, some sections exhibit a low level of automation. A significant portion of compressor equipment is based on obsolete technologies, resulting in insufficient energy efficiency and operational reliability, as well as increased environmental impact due to pollutant emissions.

Operating conditions of GTS facilities are often complicated by natural and climatic factors, the influence of groundwater and soil conditions, unauthorized interference, and, at present, military threats and terrorist attacks. The human factor plays an important role in the technological process, as operational efficiency largely depends on the level of personnel training and compliance with maintenance regulations.

The current condition and operating features of GTS facilities require a comprehensive approach to modernization, operational improvement, and the implementation of measures aimed at enhancing

reliability and safety. This approach should combine analysis of operating conditions and technical diagnostics with the deployment of modern monitoring and control systems to ensure safe, stable, and environmentally acceptable operation. The reliability and safe operation of facilities depend on the influence of a wide range of threats differing in origin and level of impact. Identification of these hazards is a necessary prerequisite for risk assessment and the development of measures to reduce their effects.

The technical condition of the equipment is characterized by various problems, including obsolete technologies, worn pipelines and compressor equipment affected by corrosion processes, defects in welded joints identified during maintenance and repairs, and, according to statistical data, failures of shut-off valves, instrumentation, and components of automation systems. Occupational injury indicators in the sector point to multiple causes, including organizational and psychophysiological factors as well as specific working conditions; however, personnel errors during operation, maintenance, or commissioning activities, often involving violations of established operating regimes, also play a significant role [10]. Fig. 1 presents statistical data on occupational injuries over the two years preceding the full-scale invasion of our territory.

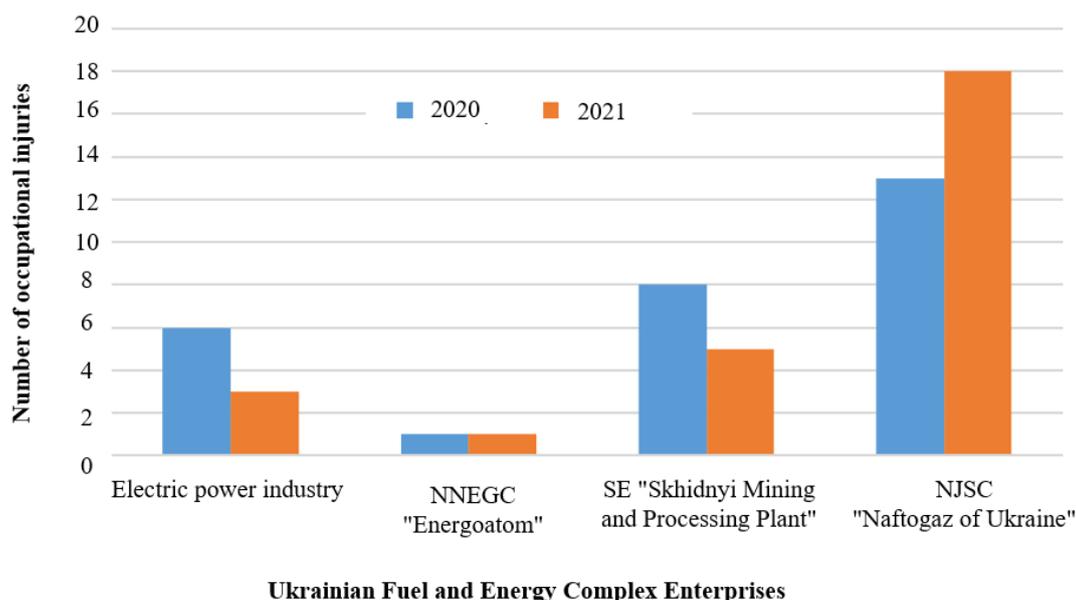


Fig. 1. Industrial accident statistics

Operational indicators of occupational injuries in the fuel and energy sector for the same periods of 2020 and 2021 at state-owned enterprises, including the oil and gas sector. During the reporting period in 2021, 11 cases of occupational injuries with fatal outcomes were recorded, which is higher than in 2020, when there were 7 cases. Year after year, the influencing factors remain the same, and potential hazards, whether explicit or hidden, persist and are reflected in reports of the relevant ministries.

There are also natural hazards affecting the operation of the gas transmission system, caused by environmental and climatic conditions. Among them, the most dangerous are landslides, flooding, erosion processes, seismic activity accompanied by sudden temperature fluctuations, heavy precipitation, and equipment icing. These factors can lead to mechanical damage to pipelines, breaches of integrity, and difficulties in accessing GTS facilities.

An insufficient level of planned preventive maintenance and untimely diagnostics of the technical condition, caused by a lack of financial and material resources, insufficient personnel qualifications, or imperfections in the management system, also affects the technological process of gas transportation. At present, this situation is further complicated by sabotage, terrorist acts, or unauthorized interference with the operation of the GTS.

Comprehensive identification of these threats allows for the determination of the most vulnerable elements of the gas transmission system, assessment of risk levels, and the development of substantiated measures to improve the reliability, safety, and resilience of GTS facilities.

When assessing hazards and their impact levels, it is necessary to select system elements, determine possible failures, evaluate their consequences, and identify their causes. The FMEA (Failure Modes and Effects Analysis) method is applied for hazard assessment at a facility. The essence of FMEA lies in identifying potential failures of

system elements and determining the causes and consequences of each failure within the technical system or the human-machine-environment system. This method allows for a quantitative risk assessment and enables the prioritization of corrective actions. FMEA is widely used in the energy sector and gas transmission systems, as well as in industrial safety management, mechanical engineering, risk management systems, and other applications.

To assess hazardous situations and determine risks in the operation of the gas transmission system, an important component of the technological process – a compressor station – was selected. The compressor station equipment consists of gas-turbine or electric-driven compressors, auxiliary cooling systems, and emergency protection systems that provide automatic shutdown of the compressor unit in case of exceeding allowable values for gas pressure at the inlet or outlet, gas temperature after the compressor, or rotor rotational speed.

The purpose of FMEA is to identify potential equipment failures, analyze their causes and consequences, and determine priority measures to enhance the reliability and safety of the compressor station. The advantage of this method lies in the early detection of critical failures, which reduces the likelihood of accidents, ensures more reliable gas transportation, and minimizes risks to personnel and the public.

There are various types and causes of equipment failures, including mechanical failures, electrical failures, automation and instrumentation (I&C) system failures, human factors, external influences, causes related to gas quality and preparation, and others. Consequences of these failures include emergency shutdowns of compressor units, reduced throughput of the main gas pipeline, gas leaks with potential fire hazards, and increased operational risks for personnel. The results of the risk analysis of the compressor station using FMEA are presented in Table 1.

Table 1

Failure Modes and Effects Analysis (FMEA) of the Compressor Station

System technological component	Failure mode	Failure causes	Effects	S	O	D	RPN
1	2	3	4	5	6	7	8
Compressor station unit	Component overheating	Cooling system failure and overload	Emergency shutdown, fire	9	4	3	108
Compressor station unit	Bearing failure	Wear, lack of lubrication	Unit failure	8	5	4	160
Gas pipeline	Gas leak	Corrosion, welding defect	Explosion, fire, threat to the population	10	3	4	120
Shut-off valves	Wear or failure of the component; casing deformation; threaded joint failure	Mechanical failure, power loss	Inability to localize the accident	9	3	5	135

End of Table 1

1	2	3	4	5	6	7	8
Cooling system	Pump failure	Wear, electrical malfunction	Gas overheating	7	4	4	112
Automated Process Control System (APCS)	No signal	Sensor failure, cable break	Delayed response	8	3	6	144
Power supply	Complete power outage	Network failure	Station shutdown	7	2	3	42

For each failure, three indicators are determined:

- S, Severity, which evaluates the seriousness of the failure consequences on a scale from 1 (insignificant) to 10 (catastrophic);
- O, Occurrence, which evaluates the likelihood of the failure occurring on a scale from 1 (very rare) to 10 (frequent);
- D, Detection, which evaluates the probability of detecting the failure before its consequences occur, on a scale from 1 (guaranteed detection) to 10 (not detectable).

The calculation of the Risk Priority Number (RPN) is carried out according to the formula:

$$RPN = S \times O \times D. \quad (1)$$

The higher the RPN value, the greater the risk. High RPN values require immediate action. The analysis of the results shows that the highest risk priority is associated with:

- compressor bearing failure (RPN = 160);
- control system failures (RPN = 144);
- valve malfunctions (RPN = 135).

These elements require the primary implementation of engineering and organizational measures. Corrective actions should also be applied to other system components. For example, in case of compressor overheating, it is necessary to provide a backup cooling system and implement online monitoring of the main operational parameters of the compressor.

Vibration diagnostics and maintenance of the compressor unit make it possible to prevent component failure. To determine the technical level and assess the condition of the compressor equipment, vibration characteristics are analyzed:

- express control of the condition of the compressor components and identification of control points with maximum vibration levels;
- assessment of the intensity of mechanical vibration sources and vibration displacement to evaluate the vibration of flexible rotors of the compressor unit;
- vibration load on bearings, gear couplings, and flow path components to refine the assessment of technical condition;
- determination of vibration characteristics to identify the causes of vibration, detect contact between

moving and stationary parts, rotor self-oscillations, resonance phenomena, and to prepare a conclusion on the operability of the compressor unit;

- determination of vibration characteristics for a more objective assessment of the technical level, justification of technically achievable vibration values, and the development of measures to reduce the intensity of main vibroacoustic sources.

Gas leaks through the pipeline body occur very frequently and with varying intensity. These leaks lead to significant economic and environmental losses, and therefore require prompt and effective detection and elimination measures. If a gas leak occurs in the pipeline, the problem must be identified as early as possible, which can be achieved through the installation of gas analyzers.

If problems arise with the shut-off valves (gate valves, valves, taps) at a compressor station or along the pipeline, actions must be taken strictly in accordance with safety rules and operational regulations. Depending on the nature of the malfunction, for example, if the valve does not operate, it is necessary to check permits and interlocks, or switch the control to manual/backup mode (if allowed by the regulations) and perform unscheduled maintenance of the seal glands by authorized personnel.

If a problematic operation is observed in the compressor unit cooling system, such as pump failure, actions should be taken step by step and according to the regulations. Specifically, reduce the load on the compressor unit (if possible); if the temperature rises to critical levels, perform a controlled shutdown of the unit and ensure airflow for ventilation in the equipment area. In case of cooling pump failure, it must be possible to switch to a backup pump and verify the restoration of key parameters, including pressure, gas flow, and temperature. Preventive measures should be implemented, including regular testing of backup pumps with monitoring of coolant quality, cleaning of filters and heat exchangers, and vibration assessment of the pumps.

Failure of the cooling system pump is a critical malfunction that can lead to overheating and damage to the compressor unit. Resolution of this failure is possible by switching to a backup pump and monitoring the equipment's operating parameters; if necessary, safe shutdown measures should be applied, followed by elimination of the causes of the failure.

In case of possible issues with the automated control system (ACS), particularly if a signal is lost (from a sensor, communication channel, or subsystem), the facility should be switched to a safe mode with reduced load and transferred to a backup circuit if provided by the process scheme. If necessary, a controlled shutdown of the unit may be performed. Typical causes of signal loss include: break or short circuit of the signal cable, failure of a pressure, temperature, or flow sensor, power loss to the sensor, or communication failure. Further actions depend on the type of signal. If it is a critical signal, startup must be prohibited, and a backup sensor or manual mode should be used if allowed by the regulations; if no backup is available, the unit must be stopped. If the technological signal is non-critical, limited operation with increased monitoring is allowed, accompanied by urgent diagnostics and repair.

Power supply issues at facilities are currently a widespread problem affecting every enterprise. Therefore, the growing interest in addressing energy supply challenges, including the use of local alternative fuels and renewable energy sources, highlights the importance of measures to develop and improve local microgrid systems.

In developed countries, local solutions relate to transformational measures that aim to change their traditional identity as passive consumers. There is experience in implementing so-called active consumers, who can act both as energy consumers and producers. Local energy systems potentially can address self-sufficiency while contributing to overall energy goals, following general trends in energy consumption [11–13].

However, when it comes to problems with equipment directly on the energy systems of a main gas pipeline, a number of typical equipment issues and potential hazards can be identified. The electrical equipment of the main gas pipelines includes transformer substations, electric motors, distribution devices, and backup power sources. They are intended to supply power to compressors, pumps, ACS, and safety systems, and the reliability and safety of the entire system largely depend on them. Therefore, it is important to separately assess possible types of failures of electrical equipment at the facility. For this purpose, the Fault Tree Analysis (FTA) method can be used.

The method is based on a logical-analytical construction used to investigate the causes of an undesired event (top event) by progressively breaking it down into intermediate and basic failures using logical elements. FTA method is an effective tool for equipment reliability analysis, allowing a systematic study of failure causes, enhancing safety, and ensuring stable operation of critical facilities, such as compressor stations of main gas pipelines.

The consequences of the top event in the diagram (Fig. 2) include an emergency shutdown of the compressor station, a reduction in the throughput capacity of the gas transmission system, and a potential risk of water hammer during restart. These outcomes can have various implications and may be reflected in financial and environmental losses (accidents or emergencies).

Based on the conducted modelling, key risk reduction measures may include both power supply redundancy and transformer duplication. Regular testing of relay protection systems and monitoring of equipment temperature under load conditions are essential. Equally important are personnel training, skills enhancement, and the standardization of operational procedures.

Natural gas transportation facilities are classified as high-hazard objects. Data on fires and accidents at gas transportation facilities are limited because these facilities have strategic significance for the national economy, and information about emergencies or accidents is not intended for wide dissemination. Based on publicly available data, representative cases of safety violations in gas supply have been presented, and the types and causes of such incidents have been analyzed [14–17]. Gas pumping units, as the primary equipment of compressor stations, pose particular fire and explosion hazards.

Emergencies and failures of technological equipment at compressor stations (CS) can occur due to a rupture of an external process gas pipeline across its full cross-section or the destruction of tanks, apparatuses, external installations, and their piping systems, which may be accompanied by the release of natural gas with or without ignition. A review of studies on defects and cracks in buried pipelines, methods for their detection, and residual life prediction is presented by the authors in [18]. This information is crucial for understanding modern methods of defect analysis and monitoring that could lead to accidents.

Research on rupture or destruction prediction methods, based on advanced scientific approaches, enables the assessment of reliability and the condition of underground gas pipelines using neural networks, allowing the forecasting of potential failures and accidents [19].

An analysis of existing issues in gas pipeline operation, related to explosions and leaks in the Baltic Sea (Nord Stream), which are critical for national energy security, is presented in [20]. These studies of international underwater infrastructure are important for analyzing pipeline failures in global energy systems, ensuring safety and reliability, and protecting the environment.

With the rapid development of pipeline integrity management technologies and the growing requirements for the safe operation of oil and gas pipelines, inspection

and monitoring technologies have received significant attention and are actively evolving. Issues related to diagnostics, inspection, and monitoring of oil and gas

pipelines, including magnetic flux leakage (MFL) technology, ultrasonic testing (UT), and other methods, are presented in the work of the authors [21].

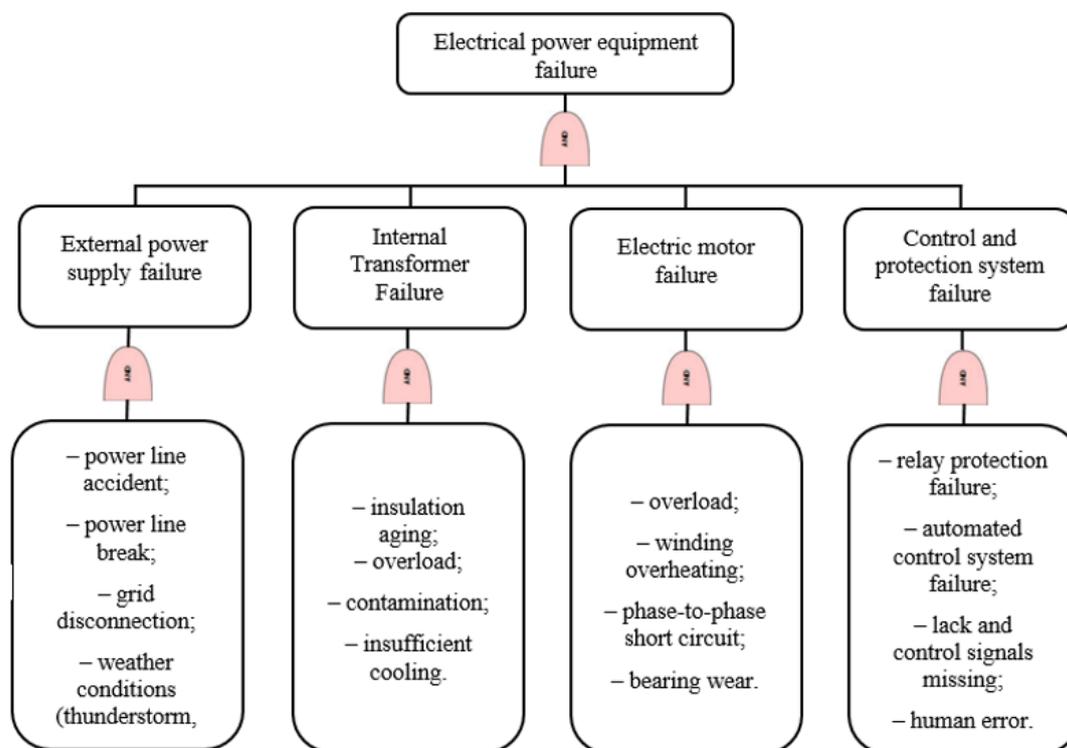


Fig. 2. Fault Tree Method in the operation of electrical power equipment at a compressor station

A monograph by the authors [22] is devoted to the issues of pipeline failure and rupture, the effects of corrosion and defects, pipeline integrity, and the fundamentals of reliability and operational safety assessment. It presents a theoretical and engineering basis for analyzing failure causes and explains how design, material, or installation errors can lead to accidents.

The main physical manifestations of such accidents and the associated damaging factors include:

- rupture or destruction of a gas pipeline accompanied by the release and ignition of a significant amount of natural gas, resulting in a jet flame or a column fire;
- rupture or destruction of a gas pipeline accompanied by the release of natural gas into the environment;
- release of natural gas into an industrial facility, leading to the formation of an explosive gas-air mixture with the risk of ignition and explosion, accompanied by a compression (blast) wave and fire.

The primary objective in gas pipeline operation is to maintain the satisfactory condition of the main gas transmission systems. Therefore, continuous

monitoring, diagnostics, preventive measures against accidents and incidents, as well as timely elimination of defects in both underground and aboveground pipeline sections, are important and urgent issues that must be addressed.

Most main gas pipelines are laid underground, which significantly exposes these pipeline sections to corrosion-active processes in soils. Under their influence, wall thinning of pipes occurs, increasing the risk of metal corrosion and leading to the occurrence of emergencies.

The primary consequence of accidents on gas pipelines is pipe rupture and the release of gas into the atmosphere. The extent of the pipe rupture and the probability of gas ignition or explosion depend on the technical parameters of the pipeline, gas pressure, and the characteristics of the soil in which the damaged pipeline section is laid.

The causes of accidents on main gas pipelines include:

- pipe metal corrosion;
- construction or manufacturing defects;
- mechanical damage during maintenance or construction works;

- design deficiencies during manufacturing or overall product defects;
- erroneous actions of personnel during operation;
- equipment wear and ageing;
- the impact of natural hazards and extreme natural phenomena.

It should be noted that the intensity and scale of gas pipeline accidents directly depend on the region through which the main pipeline is routed. Factors influencing pipeline wear include the level of industrial and transportation infrastructure development, the general climatic conditions of the region, and the availability of sufficient maintenance personnel. Among the causes of increased accident rates in gas pipelines, depending on the routing region, are:

- routing of the gas pipeline near populated areas with a high level of anthropogenic activity (construction zones, crossings with roads and railways), where a greater number of water bodies are present, resulting in an increased proportion of underwater pipeline crossings;
- the presence of a larger number of engineering utilities (water supply systems, power supply systems, etc.);
- population density and, consequently, the level of gas consumption;
- the degree of urban development of the settlement.

Statistical data on accidents within the country indicate significant differences in accident intensity across various regions. For example, a high percentage of accidents during the spring flood period has been recorded on pipeline sections laid across riverbed crossings. According to expert estimates, the accident intensity in riverbed crossing sections is approximately 5–7 times higher than that of adjacent onshore pipeline sections.

Different emergencies can have severe consequences. Explosions may result in the destruction of buildings and structures, the formation of debris, secondary explosions, and large-scale fires caused by industrial accidents. Electrical short circuits, depressurization of storage tanks containing flammable substances, the formation of hazardous zones due to toxic factors, and injuries to people and animals are also possible.

The importance and urgency of measures aimed at preventing and minimizing emergencies in the gas transmission system of Ukraine are difficult to overestimate, especially under current conditions, when, in addition to technogenic and natural threats, there is a significant impact of military aggression.

The first approach involves the implementation of an Industrial Safety Management System (ISMS), which is a comprehensive and systematic process of organizing, planning, controlling, and continuously

improving an enterprise's activities. It is aimed at preventing accidents, emergencies, and occupational injuries, as well as minimizing their consequences at high-risk facilities, including gas transmission system (GTS) facilities.

This approach includes measures for systematic hazard identification, risk assessment and management of potential accidents at the facility, clear allocation of responsibilities among management and involved personnel, and integration of this safety approach into all operational processes.

The main objective of implementing an ISMS is to reduce the probability of accidents and emergencies, protect the life and health of personnel, minimize environmental impact, ensure uninterrupted operation of the GTS, and comply with the requirements of Ukrainian legislation and international standards [23].

The development of an Emergency Localization and Response Plan (ELRP) involves the implementation and regular updating of a set of organizational and technical measures aimed at timely response to accidents, minimization of their consequences, and protection of personnel, the public, and the environment at high-risk facilities. The essence of ELRP development primarily concerns the identification of potential accident scenarios, the assessment of risks and the scale of possible consequences. Based on this, clear actions for personnel in the event of an emergency are defined, as well as effective interaction with emergency and rescue services.

For this purpose, it is necessary to understand the characteristics of the main technological processes and potential equipment failures. In addition, the application of HAZOP, FMEA, and FTA methods helps to identify major hazards and risks, assess impact zones and effects on personnel and the population, predict environmental damage, and develop strategies to counteract these undesirable events.

The technical component of accident prevention is represented by modernization and the implementation of advanced technologies and equipment, including:

- application of modern shut-off and control valves;
- redundancy of critical systems, such as the power supply;
- use of automatic protection and emergency shutdown systems;
- technical components for overpressure protection (safety relief valves);
- early gas leak detection systems;
- application of corrosion protection for pipelines;
- regular equipment diagnostics and condition monitoring.

Minimization of emergency consequences involves the application of organizational and technical approaches, including automatic isolation of damaged sections, localization of gas leaks, and installation of

emergency ventilation systems. Fire and explosion safety measures include hazardous area zoning, installation of fixed gas detectors and automatic fire suppression systems, and regular fire safety inspections.

The integrated application of organizational, technical, analytical, and emergency response measures makes it possible to reduce the probability of emergencies in the gas transmission system, minimize accident consequences, ensure the safety of personnel, the public, and the environment, and enhance the reliability and continuity of gas transportation.

### Conclusions

The article presents a comprehensive reliability analysis of facilities of the gas transmission system of Ukraine as high-risk objects under modern technogenic, natural, and military challenges. It is shown that the GTS is a critically important engineering and strategic infrastructure, the stable operation of which determines the state's energy security, economic functioning, and public safety.

It has been established that a significant portion of GTS equipment is characterized by a high level of physical and moral obsolescence, outdated automation systems, insufficient monitoring, and low energy efficiency, which significantly increases the risk of emergencies. Additional hazard factors include corrosion processes, complex natural and climatic conditions, the human factor, limited investment resources, as well as threats of sabotage and military damage.

The study substantiates the feasibility of applying modern risk and reliability analysis methods, in particular FMEA and FTA. Using a compressor station as an example, it is shown that failures of compressor unit components, control systems, and shut-off valves are the most critical, having the highest Risk Priority Number (RPN) values and requiring the priority implementation of engineering and organizational measures. Fault Tree Analysis of electrical power equipment confirmed the importance of power supply redundancy, duplication of critical elements, and improved operational quality.

It has been demonstrated that accidents on main gas pipelines have significant potential consequences for personnel, the public, and the environment, including fires, explosions, infrastructure damage, and environmental losses.

It is substantiated that improving the reliability and safety of GTS facilities is possible only through the implementation of an industrial safety management system, regular application of risk analysis methods, equipment modernization, development of automation and monitoring systems, and continuous improvement of personnel qualifications. An important role is also played by the development and regular updating of

emergency localization and response plans, taking into account realistic emergency scenarios.

Thus, the results of the study confirm the relevance of a systemic approach to reliability assessment of high-risk gas transmission system facilities and provide practical recommendations for risk reduction, minimization of emergency consequences, and ensuring safe and uninterrupted natural gas transportation under modern threats.

### References

1. Kosaretskyi, Ye., Sotnyk, V., & Sliusarenko, A. (2023). Investigation of the Impact of Military Actions on the National Economy of Ukraine: Actual Damages and Losses. Construction and Economic Substantiation of the Development of the Armed Forces, 2(78), 74–79. <https://doi.org/10.33099/2304-2745/2023-2-78/74-79>.
2. Maksymchuk, M. V. (2019). Features of organizational and economic regulation of gas distribution enterprises' activities in Ukraine at the regional level. *Ukrainian Journal of Applied Economics*, 4(4), 346–352. <https://doi.org/10.36887/2524-0455-2019-2-1>.
3. Horin, P. V., Tymkiv, D. F., & Holubenko, V. P. (2017). Systematization of methods for cleaning gas collection networks for gas transportation from mature fields. *Municipal Economy of Cities*, 134, 52–57.
4. Pavlov, K. V., Pavlova, O. M., & Korotia, M. I. (2020). Regulation of the activities of regional gas distribution enterprises of Ukraine: monograph. Lutsk: SPD Hadiak Zhanna Volodymyrivna, "Volynpolihraf" Printing House, 256 p.
5. Harmatiuk, O. (2012). Analysis of external and internal factors of the crisis state of gas supply and gasification enterprises in the Western region of Ukraine. *Socio-Economic Problems and the State*, 1(6), 31–35.
6. Lousada, S., Jankauskienė, D., Pukite, V., Zubaka, O., Roman, L., & Delehan, S. (2026). Bridging the Resilience Gap: How Ukraine's Gas Network and UGS De-Risk Europe's Sustainable Transition Beyond 2025. *Sustainability*, 18(1), 136. <https://doi.org/10.3390/su18010136>.
7. Chekurin, V., Ponomaryov, Y., Prytula, M., & Khymko, O. (2018). Development of an approach to automation of gas transmission system management. *Technology Audit and Production Reserves*, 5(1(43)), 52–60. <https://doi.org/10.15587/2312-8372.2018.146574>.
8. Havrysh, O. A., & Vyzhanov, O. S. (2024). Economic sustainability of the gas transportation system of Ukraine in the conditions of European integration processes. *Economic Achievements: Perspectives and Innovations*. <https://doi.org/10.5281/zenodo.14306198>.
9. Plakhotnyuk, N. V., & Ikonnikova, N. V. (2018). European Energy Market and Prospects of Ukraine. *Social and Legal Studies*, 1(1), 128–134. <https://doi.org/10.32518/2617-4162-2018-1-128-134>.
10. Ministry of Energy of Ukraine. The Report. Retrieved from: <https://surl.li/klgssn>.
11. Ghiani, E., Giordano, A., Nieddu, A., Rosetti, L., & Fabrizio, P. (2019). Planning of a smart local energy community: the case of Berchidda Municipality (Italy). *Energies*, 12(24), 4629. <https://doi.org/10.3390/en12244629>.

12. Koratz, Y., & Gabbar, A. (2017). Risk analysis and self-healing approach for resilient interconnect micro energy grids. *Sustainable Cities and Society*, 32, 638–653. <https://doi.org/10.1016/j.scs.2017.05.010>.
13. Johnson, M. (2017). Controlling and optimizing resilient distributed energy resources and microgrids with a demand-side operation platform. *The Electricity Journal*, 30(4), 12–15. <https://doi.org/10.1016/j.tej.2017.03.010>.
14. Han, Z. Y., & Weng, W. G. (2011). Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network. *Journal of Hazardous Materials*, 189(1–2), 509–518. <https://doi.org/10.1016/j.jhazmat.2011.02.067>.
15. Rusin, A., Stolecka-Antczak, K., Kapusta, K., Rogoziński, K., & Rusin, K. (2021). Analysis of the Effects of Failure of a Gas Pipeline Caused by a Mechanical Damage. *Energies*, 14(22), 7686. <https://doi.org/10.3390/en14227686>.
16. Liu, C. (2025). Analysis and Countermeasures of Safety Accidents in Urban Gas Pipeline Networks. *International Core Journal of Engineering*, 11(6), 211–216. [https://doi.org/10.6919/ICJE.202506\\_11\(6\).0023](https://doi.org/10.6919/ICJE.202506_11(6).0023).
17. Lam, C., Zhou, W. (2016). Statistical analyses of incidents on onshore gas transmission pipelines based on PHMSA database. *International Journal of Pressure Vessels and Piping*, 145, 29–40. <https://doi.org/10.1016/j.ijpvp.2016.06.003>.
18. Yang, M., Yuan, M., & Chen, Y. (2025). Current Status of Research on Buried Gas Pipelines Containing Crack Defects. *International Core Journal of Engineering*, 11(10), 7–11. [https://doi.org/10.6919/ICJE.202510\\_11\(10\).0002](https://doi.org/10.6919/ICJE.202510_11(10).0002).
19. Taraghi, P., Li, Y., Adeeb, S. (2025). Physics-Informed Neural Network-based Reliability Analysis of Buried Pipelines. *ArXiv:2511.11613*. <https://doi.org/10.48550/arXiv.2511.11613>.
20. Soldi, G., Gaglione, D., Raponi, S., Forti, F., d’Afflisio, E., Kowalski, P.,...Warner, C. (2023). Monitoring of Underwater Critical Infrastructures: the Nord Stream and Other Recent Case Studies. *ArXiv:2302.01817*. <https://doi.org/10.48550/arXiv.2302.01817>.
21. Yu-zhong, L., Hong-li, Z., Shi-min, J., Quan-li, L., Kai-fu, D., Jin-quan, Z. (2012). Status of Oil & Gas Pipeline Inspection and Monitoring both at Home and Abroad. *Petroleum Science and Technology Forum*, 31(2), 30–35. <https://doi.org/10.3969/j.issn.1002-302x.2012.02.007>.
22. Mohitpour, M., Golshan, H., Murray, A. (2007). Pipeline Design and Construction: A Practical Approach. New York : ASME Press, 734 p.
23. DSTU ISO 45001:2019 Occupational health and safety management systems. Requirements with guidance for use (ISO 45001:2018, IDT). Retrieved from: [https://zakon.isu.net.ua/sites/default/files/normdocs/dstu\\_iso\\_45001\\_2019.pdf](https://zakon.isu.net.ua/sites/default/files/normdocs/dstu_iso_45001_2019.pdf).
- підприємств в Україні на регіональному рівні / М. В Максимчук // Український журнал прикладної економіки. – 2019. – Том 4. № 4. – С. 346–352. – DOI: 10.36887/2524-0455-2019-2-1.*
3. Горін П. В. Систематизація методів очистки газозбірних мереж для транспортування газу зрілих родовищ / П. В. Горін, Д. Ф. Тимків, В. П. Голубенко // Комунальне господарство міст. – 2017. – Вип. 134. – С 52–57.
4. Павлов К. В. Регулювання діяльності регіональних газорозподільних підприємств України : монографія / К. В. Павлов, О. М. Павлова, М. І. Коротя. – Луцьк: СПД Гадяк Жанна Володимирівна, друкарня «Волиньполіграф», 2020. – 256 с. [https://evnuir.vnu.edu.ua/bitstream/123456789/21744/1/koroti\\_a\\_2020.pdf](https://evnuir.vnu.edu.ua/bitstream/123456789/21744/1/koroti_a_2020.pdf)
5. Гарматюк О. Аналіз зовнішніх та внутрішніх чинників кризового стану підприємств з газопостачання та газифікації Західного регіону України / О. Гарматюк // Соціально-економічні проблеми і держава. – 2012. – Вип. 1(6). – С. 31–35. <https://sepd.mtu.edu.ua/images/stories/pdf/2012/12goozru.pdf>
6. Bridging the Resilience Gap: How Ukraine’s Gas Network and UGS De-Risk Europe’s Sustainable Transition Beyond 2025 / S. Lousada, D. Jankauskienė, V. Pukite (eds.) // Sustainability. – 2026. – Vol. 18(1) : 136. – DOI: 10.3390/su18010136.
7. Розроблення підходу до автоматизації управління газотранспортною системою / V. Chekurin, Y Pomaryov, M. Prytula, O. Khymko // Technology Audit and Production Reserves. – 2018. – Том 5, № 1(43). – С. 52–60. – DOI: 10.15587/2312-8372.2018.146574.
8. Гавриш О. А. Економічна стійкість газотранспортної системи України в умовах євроінтеграційних процесів / О. А Гавриш., О. С. Вижанов // Здобутки економіки: перспективи та інновації. – 2024. – DOI: 10.5281/zenodo.14306198.
9. Плахотнюк Н. В. Європейський енергетичний ринок та перспективи України / Н. В. Плахотнюк, Н. В. Іконнікова // Соціально-правові студії. – 2018. – Вип. 1. – С. 128–134. – DOI: 10.32518/2617-4162-2018-1-128-134.
10. Міністерство енергетики України. Звіт. – Режим доступу: <https://surl.li/klgssn>.
11. Planning of a smart local energy community: the case of Berchidda Municipality (Italy) / E. Ghiani, A. Giordano, A. Nieddu (eds.) // Energies. – 2019. – Vol. 12(24) : 4629. – DOI: 10.3390/en12244629.
12. Koratz Y. Risk analysis and self-healing approach for resilient interconnect micro energy grids / Y. Koratz, A. Gabbar // Sustainable Cities and Society. – 2017. – Vol. 32. – P. 638–653. – DOI: 10.1016/j.scs.2017.05.010.
13. Johnson M. Controlling and optimizing resilient distributed energy resources and microgrids with a demand-side operation platform / M. Johnson // The Electricity Journal. – 2017. – Vol. 30(4). – P. 12–15. – DOI: 10.1016/j.tej.2017.03.010.
14. Han Z. Y. Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network / Z. Y. Han, W. G. Weng // Journal of Hazardous Materials. – 2011. – Vol. 189(1–2). – P. 509–518. – DOI: 10.1016/j.jhazmat.2011.02.067.

## Література

1. Косарецький Є. Дослідження впливу воєнних дій на національну економіку України: фактичні збитки та втрати / Є. Косарецький, В. Сотник, А. Слюсаренко // Будівництво та економічне обґрунтування розвитку збройних сил. – 2023. – № 2(78). – С. 74–79. DOI: 10.33099/2304-2745/2023-2-78/74-79.
2. Максимчук М. В. Особливості організаційно-економічного регулювання діяльності газорозподільних

15. Analysis of the Effects of Failure of a Gas Pipeline Caused by a Mechanical Damage / A. Rusin, K. Stolecka-Antczak, K. Kapusta (eds.) // *Energies*. – 2021. – Vol. 14(22) : 7686. – DOI: [10.3390/en14227686](https://doi.org/10.3390/en14227686).
16. Liu C. Analysis and Countermeasures of Safety Accidents in Urban Gas Pipeline Networks / C. Liu // *International Core Journal of Engineering*. – 2025. – Vol. 11(6). – P. 211–216. – DOI: [10.6919/ICJE.202506\\_11\(6\).0023](https://doi.org/10.6919/ICJE.202506_11(6).0023).
17. Lam C. Statistical analyses of incidents on onshore gas transmission pipelines based on PHMSA database / C. Lam, W. Zhou // *International Journal of Pressure Vessels and Piping*. – 2016. – Vol. 145. – P. 29–40. – DOI: [10.1016/j.ijpvp.2016.06.003](https://doi.org/10.1016/j.ijpvp.2016.06.003).
18. Yang M. Current Status of Research on Buried Gas Pipelines Containing Crack Defects / M. Yang, M. Yuan, Y. Chen // *International Core Journal of Engineering*. – 2025. – Vol. 11(10). – P. 7–11. – DOI: [10.6919/ICJE.202510\\_11\(10\).0002](https://doi.org/10.6919/ICJE.202510_11(10).0002).
19. Taraghi P. Physics-Informed Neural Network-based Reliability Analysis of Buried Pipelines / P. Taraghi, Y. Li, S. Adeb // *ArXiv:2511.11613*. – 2025. – DOI: [10.48550/arXiv.2511.11613](https://doi.org/10.48550/arXiv.2511.11613).
20. Monitoring of Underwater Critical Infrastructures: the Nord Stream and Other Recent Case Studies / G. Soldi, D. Gaglione, S. Raponi (eds.) // *ArXiv:2302.01817*. – 2023. – DOI: [10.48550/arXiv.2302.01817](https://doi.org/10.48550/arXiv.2302.01817).
21. Status of Oil & Gas Pipeline Inspection and Monitoring both at Home and Abroad / L. Yu-zhong, Z. Hong-li, J. Shi-min (eds.) // *Petroleum Science and Technology Forum*. – 2012. – Vol. 31(2). – P. 30–35. – DOI: [10.3969/j.issn.1002-302x.2012.02.007](https://doi.org/10.3969/j.issn.1002-302x.2012.02.007).
22. Mohitpour M. Pipeline Design and Construction: A Practical Approach / M. Mohitpour, H. Golshan, A. Murray. – New York : ASME Press, 2007. – 734 p.
23. ДСТУ ISO 45001:2019. Системи управління охороною здоров'я та безпекою праці. Вимоги та настанови щодо застосування (ISO 45001:2018, IDT). – Чинний від 2021–01–01. – Київ : ДП «УкрНДНЦ», 2019. – 39 с. – Режим

доступу:

[https://zakon.isu.net.ua/sites/default/files/normdocs/dstu\\_iso\\_45001\\_2019.pdf](https://zakon.isu.net.ua/sites/default/files/normdocs/dstu_iso_45001_2019.pdf).

**Рецензент:** д-р техн. наук, проф. С. М. Логвінков, Харківський національний університет міського господарства імені О. М. Бекетова, Україна

**Автор:** МОРОЗ Микола Олександрович  
кандидат технічних наук, доцент, доцент кафедри  
Харківський національний університет міського господарства імені О. М. Бекетова

E-mail – [ssekret@ua.fm](mailto:ssekret@ua.fm)

ID ORCID: <https://orcid.org/0000-0002-0852-2677>

**Автор:** МИХАЙЛОВА Євгенія Олександрівна  
кандидат технічних наук, доцент, доцент кафедри  
Харківський національний економічний університет імені Семена Кузнеця

E-mail – [mykhailova.e@ukr.net](mailto:mykhailova.e@ukr.net)

ID ORCID: <https://orcid.org/0000-0002-0182-0823>

**Автор:** ШАВКУН В'ячеслав Михайлович  
кандидат технічних наук, доцент, доцент кафедри  
Харківський національний університет міського господарства імені О. М. Бекетова

E-mail – [vm.shavkun@gmail.com](mailto:vm.shavkun@gmail.com)

ID ORCID: <https://orcid.org/0009-0005-9069-7378>

## АНАЛІЗ НАДІЙНОСТІ ОБ'ЄКТІВ ПІДВИЩЕНОЇ НЕБЕЗПЕКИ ТА ОЦІНКА НАСЛІДКІВ НАДЗВИЧАЙНИХ СИТУАЦІЙ ДЛЯ НАСЕЛЕННЯ

М.О. Мороз<sup>1</sup>, Є.О. Михайлова<sup>2</sup>, В.М. Шакун<sup>1</sup>

<sup>1</sup>Харківський національний університет міського господарства імені О. М. Бекетова, Україна

<sup>2</sup>Харківський національний економічний університет імені Семена Кузнеця, Україна

У статті детально розглянуто питання надійності та безпеки об'єктів підвищеної небезпеки газотранспортної системи (ГТС) в умовах сучасних техногенних, природних та воєнних загроз. Проведено комплексний аналіз технічного стану магістральних газопроводів, компресорних станцій та допоміжного обладнання, визначено основні чинники, що впливають на виникнення аварійних ситуацій та надзвичайних подій. Особлива увага приділяється зношеності інфраструктури, моральному та фізичному старінню обладнання, застарілим системам автоматизації, людському фактору, а також впливу зовнішніх ризиків, включаючи кліматичні умови, корозійні процеси, географічні особливості прокладки трубопроводів та можливі загрози диверсійного чи воєнного характеру.

У роботі застосовано сучасні методи аналізу надійності та оцінки ризиків, зокрема FMEA (аналіз типових відмов та їхніх наслідків) та FTA (дерево відмов), для ідентифікації потенційних відмов обладнання, визначення їхніх причин і наслідків, а також пріоритезації заходів щодо усунення або зниження ризиків. На прикладі компресорної станції визначено найбільш критичні елементи системи, відмови яких можуть призвести до значних техногенних, екологічних і соціальних наслідків. Проаналізовано можливі сценарії аварій на магістральних газопроводах та їхній вплив на персонал, населення та навколишнє

середовище, що підкреслює необхідність комплексного підходу до управління ризиками та планування заходів з локалізації надзвичайних ситуацій.

Обґрунтовано доцільність впровадження системи управління промисловою безпекою, модернізації обладнання, розвитку автоматизованих систем моніторингу та аварійного захисту, резервування критично важливих компонентів, а також підвищення рівня кваліфікації персоналу. Велике значення надається розробленню та регулярному оновленню планів локалізації і ліквідації аварійних ситуацій, що враховують реальні сценарії надзвичайних подій і забезпечують ефективну взаємодію персоналу з аварійно-рятувальними службами. Підкреслено, що надійність і безпека ГТС залежать не лише від технічних рішень, а й від організаційних заходів та людського фактору. Чіткий розподіл відповідальності, інтеграція системи безпеки у всі виробничі процеси та підвищення підготовки персоналу є ключовими умовами мінімізації ризиків та запобігання аварій. Запропоновані підходи спрямовані на зниження ймовірності аварій, мінімізацію наслідків надзвичайних ситуацій, забезпечення безперервної та безпечної роботи ГТС. Результати дослідження формують практичні рекомендації щодо підвищення промислової безпеки, ефективного управління ризиками, захисту персоналу, населення та довкілля, а також забезпечення стабільного і надійного транспортування природного газу в умовах сучасних викликів, включаючи техногенні, природні та воєнні загрози.

**Ключові слова:** газотранспортна система, об'єкти підвищеної небезпеки, надійність, промислова безпека, оцінка ризиків, надзвичайні ситуації.

*Дата надходження статті: 16.01.2026*

*Дата прийняття до друку: 14.03.2026*

*Дата публікації статті: 23.03.2026*

*Автори заявляють про відсутність конфлікту інтересів.*