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DEVELOPMENT OF AN APPROACH TO RISK MANAGEMENT IN THE SAFETY SYSTEM OF TECHNOGENIC OBJECTS

Purpose. Development of a risk management process for complex hazardous events in safety management systems of technogenic facilities.

Methodology. To develop the process of managing risks caused by a complex of hazardous events, the most common "Bow-Tie" model was taken as a basis, which allows determining a cause-and-effect relationship between a hazard, a hazardous event and the severity of the consequences.

Findings. The model of cause-and-effect relationship between the occurrence of a primary hazardous event and the severity of consequences from each secondary hazardous event triggered by the primary one has been improved. A risk management process has been developed for safety management systems of technogenic facilities. The process consists of eight steps and includes a specific feature which differs from the known identification of secondary hazardous events and associated hazardous factors that emerge as a result of a primary hazardous event. To determine the severity scale of consequences, it is proposed to assess the damage caused to the sustainable functioning of the infrastructure of a given facility, taking into account the costs of accident localization and elimination, as well as environmental harm.

Originality. The approach involves the development of a risk management process that accounts for complex hazardous events in safety management systems of technogenic facilities. Unlike the existing approaches, this process includes an assessment of the severity of consequences resulting from a primary hazardous event.

Practical value. It consists in the development of a risk management process for hazards and losses within a safety management system, caused by a complex of hazardous events. This process differs from the known approaches by additionally identifying losses resulting from secondary hazards that manifest after the occurrence of a primary hazardous event.

Keywords: *technogenic objects, risk, hazardous event, safety management*

Introduction. In the activities of any organization, events or phenomena arise during the implementation of tasks and functions that can affect its efficiency and effectiveness. These events should be viewed either from the perspective of creating new additional opportunities or, conversely, from the perspective of risks caused by negative events. Moreover, there are internal and external circumstances that provoke the emergence of opportunities or risks [1]. Therefore, the management of the organization needs to have reliable information about the opportunities and risks for timely response to events that occur during their activities, which may have positive, negative or mixed consequences. The absence of such information often leads to missed opportunities, which will affect the organization's profits. Whereas untimely, erroneous or absent decisions due to lack of information cause the realization of risk: the occurrence of a hazardous event that leads to significant losses. Complex hazardous events characteristic of technogenic emergencies pose a particular threat. They are characterized by several damaging factors, each of which can lead to new hazardous events and corresponding additional negative consequences [2]. In existing risk management processes (methods, algorithms) described in IEC/ISO 31010:2019 (the most popular are Fault Tree Analysis, Hazard and Operability Study, Bow-Tie Analysis, Event Tree Analysis), it is assumed that each hazardous event leads to corresponding consequences, which are determined during the analysis of the cause-and-effect relationship between the hazard and the hazardous event. However, the risk assessment methods described above do not provide for determining the severity of the consequences of secondary hazardous events. For example, classical approaches (Fault Tree Analysis, Event Tree Analysis) allow modelling the sequence of events, analysing the probability of scenarios developing, and assessing the consequences of events in general terms. However, the consequences of secondary events (for example, from an explosion: shock wave, toxic gases) are not considered as separate sources of new risks. Furthermore, the severity of the consequences is not decomposed into economic, environmental and social losses in the classical approaches mentioned above. In addition, no quantitative assessment of each secondary factor separately is performed, which may increase the total risk level [3]. This raises the task of developing new or improving existing models of cause-and-effect relationships that would allow risk to be identified as a combination of the probability of a primary hazardous event occurring and the severity of the consequences of secondary hazardous events. This will reduce uncertainty in risk level calculations and improve the effectiveness of substantiating precautionary and protective measures to reduce the degree of severity of each secondary hazardous event.

Literature review. In [4], a methodology for assessing risks in tunnel construction is discussed, which is based on a combination of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). The authors emphasize that most adverse events in tunnel construction occur during the construction phase, resulting in economic losses and delays. The proposed approach allows for quantitative assessment of risks by modelling both the causes of hazards (FTA) and possible scenarios for their development (ETA). The methodology is based on graphical and mathematical (probabilistic) models that provide a qualitative assessment of risks for managerial decision-making. Unfortunately, the presented research does not take into account that the primary hazardous event can generate multiple secondary hazardous factors, each of which has its own consequences and can increase the total risk. This limits the accuracy of risk assessment and the effectiveness of management decisions.

In [5], the authors investigate the potential environmental hazard posed by closed gas stations. When analysing soil and groundwater pollution, the authors focus on the total risk management process, to which the decision-making capability is added. However, the paper does not provide a model for determining the cause-and-effect relationships between a hazard, a hazardous event, and consequences, which is recommended for use in risk management. In [6], examples of the application of the FTA method in real disasters are given: Piper Alpha, Boeing 737 MAX, Fukushima. The author compares FTA methods with FMEA and HAZOP based on the algorithm for determining top events, system analysis, failure identification, quantitative assessment of probabilities, and development of risk mitigation measures. However, despite the use of several methods for risk analysis, the author does not consider the possible increase in the severity of the consequences from the occurrence of hazardous events, which may lead to an underestimation of the total risk. In [7], an algorithm has been developed for assessing risks associated with industrial accidents involving the release of large amount of gasoline at a petrochemical plant. The authors identified the impact of individual elements of the safety management system for comprehensive risk assessment on the scale of a possible emergency situation. Moreover, the probability of a dangerous situation occurring is determined through the prism of the human factor. In [8], the authors offer a comprehensive approach to identifying risks at industrial enterprises by grouping risks depending on the scope of their occurrence. According to the authors, this allows one, using a complex-synergetic approach to risk management, to ensure the optimal development of an industrial enterprise in conditions of economic uncertainty. At the same time, no explanation is provided as to what a comprehensive approach to risk identification, implemented through risk grouping, actually is. In [9], a mechanism for managing risks at machine-building enterprises in modern business conditions is described, which is based on a hierarchical structure of hazards. Despite the fact that the author emphasizes the need, in order to choose risk analysis methods, to take into account the depth of calculated data and the horizon of predictive indicators that allow determining the level of risk complexity, the issues of assessing additional vulnerable hazards that are interrelated with the main hazard remains unresolved. In [10], the authors analyse the Bow-Tie Analysis tool for risk management in safety systems, particularly in production processes where there is a threat of technogenic accidents. They suggested using Bow-Tie not only for risk assessment, but also as a crisis management tool to prioritize and optimize response measures. The above-mentioned approach to the analysis was also improved by adding a stage for substantiating control measures and barriers, both precautionary and restorative ones. However, a hazardous event was not considered as a complex one, which can lead to the occurrence of other additional hazardous events.

The analysis of the latest scientific publications on the risk management process development of hazards and losses in safety management systems has confirmed the existence of certain shortcomings in risk assessment and management, caused solely by the consideration of a single hazardous event (for example, a natural gas explosion in a building). Existing approaches to risk assessment do not take into account that the primary hazardous event is the source of occurrence of secondary hazardous events with different degrees of severity, which are characteristic of modern technogenic accidents. This requires the development of a new risk management process, as well as an algorithm of actions based on a model of cause-and-effect relationships, taking into account the primary hazardous event and the occurrence of secondary hazardous events with varying degrees of severity of consequences.

The **purpose of the paper** is to develop a risk management process for complex hazardous events in safety management systems for technogenic facilities.

To achieve the purpose set, it is necessary to solve the following tasks:

- improvement of the cause-and-effect model "hazard – complex hazardous event – consequences", characterized by the occurrence of additional hazardous events with corresponding technogenic consequences for the environment;

- development of a risk management process for complex hazardous events, which includes a stage for determining the total damage from all hazardous events arising from the hazard;

- assessment of risks from three types of losses using the example of a technogenic accident – fuel explosion when it is drained from a tanker truck into stationary tanks at a gas station (GS).

Methods. The safety management system improved the risk and loss management process using the example of a gas station and the "Bow-Tie" method [11, 12]. This method, based on the cause-and-effect relationship between a hazard and a hazardous event, allows risks to be described and analysed during any non-compliances or threats. It can be used to determine the effectiveness of proposed "barriers" (precautionary or protective measures) in reducing the probability of a dangerous situation occurring, on the one hand, and on the other, the severity of the consequences of an incident occurring. In general, the presented method assumes the following for calculating the risk level: identifying non-compliances and threats in order to develop a register of these within the organization; determining the mechanisms for the development of a hazardous event based on cause-and-effect relationship; determining the degree of probability of a dangerous event occurring – by processing statistical data on all incidents that have occurred anywhere; determining the severity of losses by assessing the material equivalent of realized damage; calculating professional risk – by any suitable method specified in IEC 31010:2019 Risk management – Risk assessment techniques.

The method is based on the use of an improved model of cause-and-effect relationship between hazard, complex hazardous event and consequences, which allows us to represent the relationship between the realized primary hazardous event and secondary hazardous events, characterized by a variety of damaging hazardous factors (Fig. 1).

A hazard (for example, a gas cylinder) under the influence of certain hazardous factors (human, technical, operational) can lead to a primary hazardous event – an explosion, which will create secondary hazardous events: shock wave, thermal radiation from a fireball, debris, toxic gases. These secondary hazardous events

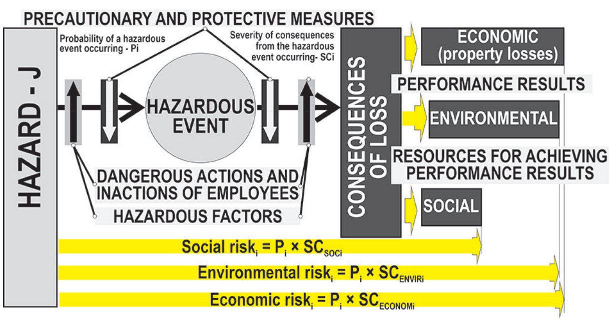

Fig. 1. "Bow-Tie" model for determining the cause-and-effect relationship between hazard, hazardous event and consequences

will result in economic, environmental and social losses related to infrastructure destruction and the need to restore it, environmental consequences – pollution of the surrounding area, social losses – loss of life or damage to human health. Unlike classical approaches, the proposed improved model clearly distinguishes between the primary hazardous event and multiple secondary damaging factors (shock wave, thermal radiation, toxic dispersion) that are their source. This allows for systematic analysis, quantification and assessment of risks and their consequences, which are not sufficiently taken into account in standard risk management models.

Research results. Consider the hazard of handling fuel transported or stored at the appropriate gas stations. Errors with its storage can lead to the occurrence of a hazardous event – a fuel vapor explosion. In this case, the explosion of the fuel-air mixture is dangerous due to the simultaneous action of several destructive forces: shock wave, thermal radiation, formation of toxic gases and scattering of fragments of destroyed objects. Since these destructive forces act simultaneously, strengthening each other, the key task is to determine a single zone of damage. It is in this zone that their combined impact poses the greatest threat to human life and the integrity of buildings (Fig. 2).

Thus, the task arises of determining the complex consequences – damage caused by all destructive forces leading to death or injury to people, infrastructure destruction and environmental pollution.

Each hazardous event – j generates three corresponding risks: infrastructure destruction; environmental damage with associated losses; loss of human life and health, as determined by the model [13]

$$R_j^{inf} = \sum_{i=1}^{n} \left(B_{ji} \times TH_{ji}^{inf} \right);$$

$$R_j^{env} = \sum_{i=1}^{n} \left(B_{ji} \times TH_{ji}^{env} \right);$$

$$R_j^{lh} = \sum_{i=1}^{n} \left(B_{ji} \times TH_{ji}^{lh} \right),$$

where $R_j^{inf}; R_j^{env}; R_j^{lh}$ are risk level: infrastructure destruction; environmental damage and losses; loss of human life and health caused by a complex hazardous

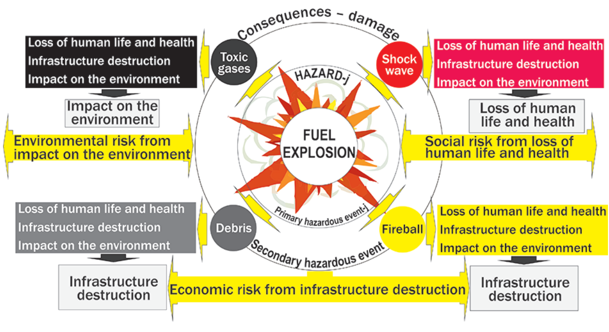

Fig. 2. Model of cause-and-effect relationship between hazard (fuel) – complex hazardous event (fuel explosion) and technogenic consequences (destruction of infrastructure, loss of life and health of employees, environmental pollution)

Table 1

Severity of consequences from the explosion of a hazardous substance

No.	Severity of consequences from the explosion	Characteristics of hazardous zones	Score
1	Insignificant damage to the organization's property and infrastructure, no damage to civilian infrastructure of the population, no casualties among employees and the population	The level of damage does not exceed 1 % of the organization's total revenue	1
2	Minor damage to the organization's property and infrastructure, slight damage to civilian infrastructure, the presence of minor injuries to personnel, no fatalities among personnel and no casualties among the civilian population	The level of damage does not exceed 10 % of the organization's total revenue	2
3	Moderate damage to the organization's property and infrastructure, moderate damage to civilian infrastructure, serious injuries to personnel, no civilian casualties, presence of minor injuries to civilian population	The level of damage does not exceed 25 % of the organization's total revenue	3
4	Significant damage to the organization's property and infrastructure, moderate damage to civilian infrastructure, the presence of fatal injuries to personnel, the presence of minor/moderate injuries among the civilian population	The level of damage does not exceed 50 % of the organization's total revenue	4
5	Catastrophic damage to the organization's property and infrastructure, significant damage to civilian infrastructure, the presence of fatal injuries to personnel, severe injuries among the civilian population	The level of damage does not exceed 100 % of the organization's total revenue	5
6	Catastrophic damage to the organization's property and infrastructure, civil infrastructure, the presence of fatal injuries to personnel and among the civilian population	The level of damage exceeds 100 % of the organization's total revenue	6

event – a fuel explosion, which poses a hazard j and hazardous factors i (air shock wave, powerful heat radiation, volume of gaseous products and flying fragments from destroyed buildings); B_{ji} is probability of occurrence of a hazardous event j under the influence of hazardous factors; $TH_{ji}^{inf}; TH_{ji}^{env}; TH_{ji}^{lh}$ are the corresponding consequences of a complex hazardous event: infrastructure destruction, environmental damage, and loss of human life and health.

To assess the severity of consequences, it is proposed to introduce a six-point scale (Table 1), which bridges the gap between technical risk assessment and strategic management (that is, the scale for assessing the severity of consequences is not too complex, detailed for managers who need to use risk assessment data to make strategic decisions). By linking specific physical damage scenarios (for infrastructure, environment and human health) to a quantitative financial threshold – a percentage of the total revenue of the organization – a scalable, business-relevant criterion for determining risk acceptability is proposed. This approach goes beyond traditional methodology and aligns safety risk with economic risk at enterprise level.

To determine the limit of acceptable risk level, it is proposed to calculate the areas of zones affected by the damaging hazardous factors of the primary hazardous event (Fig. 3).

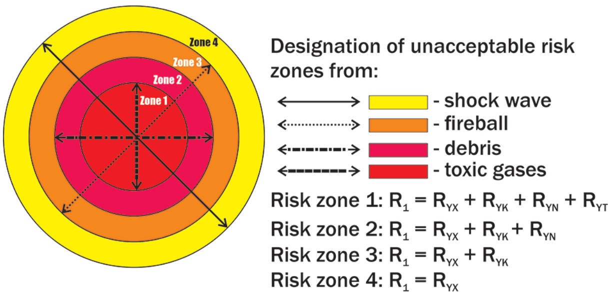

Fig. 3. Unacceptable risk limits calculated for zones affected by the damaging hazardous factors of the primary hazardous event

According to these, if necessary, it is possible to identify total losses, which are largely specified in [12], as financial losses:

- caused to the sustainable functioning of infrastructure, taking into account the costs of localization and liquidation of the accident (L_i);
- ecological damage caused by pollution of the atmosphere, surface waters, soils and resources, in particular land, water, wildlife or protected flora and fauna, forest fund or vegetation (L_{ec});
- caused by the loss of life or health of the facility personnel (L_p).

The total loss is calculated using the following formula

$$L_t = L_i + L_{ec} + L_p.$$

To calculate the above components of total damage, you can use the Methodology for assessing damage from the consequences of natural and technogenic emergencies, approved by Resolution of the Cabinet of Ministers of Ukraine No. 862 dated 4 June 2003 (or the methodology of the Ministry of Emergency Situations of 2022).

Based on the presented model (Fig. 2), a risk management process of complex hazardous events in safety management systems for technogenic facilities with various types of losses is proposed, presented in Fig. 4. Its difference from the known ones is the identification of the severity of the consequences: economic, environmental ones and those for human life and health from each identified hazard, taking into account the impact of various hazardous factors inherent in hazard.

The novelty of the risk management process of complex hazardous events in safety management systems for technogenic facilities is the mandatory risk decomposition, which requires a separate quantitative assessment for each secondary damaging factor according to three different vectors of consequences (infrastructure, environmental, human). This differential approach provides a comprehensive assessment, preventing underestimation of total risk by systematically considering all factors and their various influences.

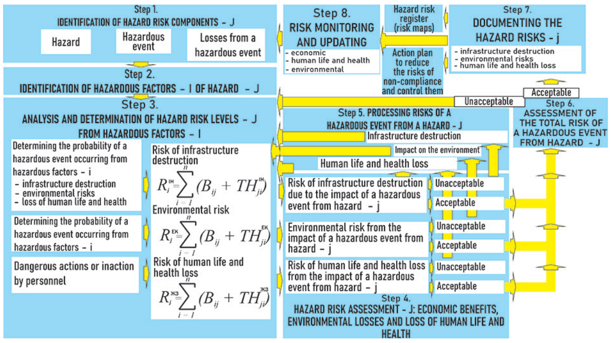

Fig. 4. Algorithm for managing risks from complex hazardous event – j

Below, each step (algorithm or procedure) of risk management is described.

Step 1. Identification of hazard risk components. The first step involves identifying key threats and hazardous risk factors, in particular: a potentially hazardous event and its possible consequences – damage to infrastructure, environmental losses, threats to human life and health. It is important to determine the cause-and-effect relationships between the threat, the event, and its impact on the functioning of the organization [10].

Step 2. Identification of hazardous factors. The next step is a detailed analysis of hazardous factors – actions or inactions that can trigger the occurrence of a hazardous event and exacerbate its consequences. For this, methods such as SWOT, PEST, PIMS analysis, as well as questionnaires, observations, staff surveys, group discussions, etc. can be used [11].

Step 3. Risk assessment. At this step, the risks arising from the identified hazards are assessed. The total risk level for each hazardous factor is determined taking into account the actions or inaction of personnel. For each threat, the risks of secondary events are additionally calculated, such as infrastructure destruction, environmental losses, threats to life and health, and environmental pollution. For this purpose, scales of probability and severity of consequences are used, which can be constructed based on the EN IEC 31010:2022 standard recommendations.

Step 4. Determining risk acceptability. An analysis of the calculated risk level is performed separately for each type of consequences — infrastructural, environmental, and social. The results of the analysis are compared with the acceptance criteria specified by the organization [13]. This research proposes a critical acceptance threshold of 60 scores for a 6 × 10 matrix.

Step 5. Risk management decision-making. If the risk level exceeds the critical threshold, precautionary measures are proposed to reduce the risk by reducing the probability of the event or the severity of its consequences. After the implementation of precautionary measures, a repeated risk assessment is performed, and, if acceptable, the process proceeds to the next step.

Step 6. Calculation of the total risk level. If the risk level from each hazardous factor is acceptable, the total risk is calculated and compared with the total acceptability limit determined from all possible total losses.

Step 7. Risk documentation. We document risk levels by creating hazard and hazardous factor registers, indicating potential consequences. Risk maps are completed, recording the results of the initial assessment and then, taking into account the precautionary and protective measures implemented, the residual risk. An action plan for periodic risk identification is developed. The form for identifying all hazards, considering the influence of hazardous factors (HF), analysing and assessing the risk from hazards for each negative consequence to determine the risk level (both acceptable and unacceptable) is given in Table 2.

Step 8. Risk monitoring. We develop a risk monitoring procedure. Its essence, according to ISO 31000:2018, is to periodically review the risk management process and its results. Review is conducted at all stages of the risk management process. It involves planning, collecting and analysing information, documenting results and providing feedback through created information channels that allow important information to be obtained quickly.

The risk assessment for three types of losses can be conducted using the example of a technogenic accident – fuel explosion when it is drained from a tanker truck into stationary tanks at a gas station. The input data for the gas station are shown in Table 3.

To calculate the radii of infrastructure destruction zones from shock waves, radiation intensity and pollution by gaseous products from the explosion of a hazardous substance specified in Fig. 2, it is proposed to use the ALOHA software, which links source power models with dispersion models to estimate the spatial extent of flammable vapours and explosion-hazardous vapour clouds [13]. To do this, enter the following parameters:

- source characteristics: type and geometric parameters of the container/tank;
- chemical substance properties: type, volume or mass;
- other key parameters influencing the substance dispersion.

Technical characteristics of the tank at the gas station: diameter: 1.7011 m, length: 11 m, volume: 25,000 l under various environmental conditions (air temperature ranging from 0 to 30 °C; wind speed from 0 to 20 m/s) [14]. The level of possible damage is determined by the force of the explosion, which is simulated using the ALOHA software.

A step-by-step analysis to identify the consequences of a hazardous event and determine the total risk level for each loss is presented in Table 4. At a gas station, the main operations involving hazardous substances include three main processes. The first is fuel reception, which is carried out by draining fuel and lubricants from tanker trucks into the station's tanks. The second is fuel storage in special tanks. The third is refuelling vehicles through fuel dispensers, which is the main stage of releasing fuel to the final consumer. The tanker truck destruction as well as gasoline leakage is the most serious potential hazard. If fuel vapours reach an explosion-hazardous concentration and a spark appears, this will cause an explosion, the scale of which depends on the volume of the spill. Although an explosion inside a tank is less powerful, the consequences can still be catastrophic.

Investing in precautionary measures to prevent such accidents is financially sound, as the costs of dealing with the consequences far exceed those of advance planning and safety measures.

Discussion. In today's world, predicting dangerous situations is an extremely important task [15], as it helps to avoid economic losses, human casualties and environ-

Table 2

Hazard identification form – j, HF, analysis and assessment of risk from hazard – j provided that the risk level is acceptable A_c/unacceptable U_n for the HF consequences: infrastructure destruction losses, loss of human life and health, and environmental hazards

Hazard No.	Identification				Primary analysis – determining the risk level for each HF and the risk, as well as assessing the risk in terms of economic, environmental, loss of life and health of employees									
	Hazard	Hazardous event	Negative consequences of economic and environmental losses, as well as loss of human life and health	Influence on the probability of a hazardous event occurring and/or on the severity of the hazardous event consequences	Probability of a hazardous event occurring from HF for each negative consequence	Degree of severity from the hazardous event occurrence for each *HF* for each negative consequence			Risk level of a hazardous event occurring for each HF for each negative consequence			Hazard risk assessment – j for each HF – i for each negative consequence		
						Infrastructure destruction	Loss of life and health of personnel	Environmental	Infrastructure destruction	Loss of life and health of personnel	Environmental	Infrastructure destruction	Loss of life and health of personnel	Environmental
j	Hazards in the workplace	Accident during production activities	Disruption of the normal economic and financial activities of the organization, disruption of life in the ecosystem of trauma, occupational diseases resulting from accidents	HF_1	P_{j1}	Tec_{j1}	Teh_{j1}	Ti_{j1}	Rec_{j1}	Reh_{j1}	Ri_{j1}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_2	P_{j2}	Tec_{j2}	Teh_{j2}	Ti_{j2}	Rec_{j2}	Reh_{j2}	Ri_{j2}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_3	P_{j3}	Tec_{j3}	Teh_{j3}	Ti_{j3}	Rec_{j3}	Reh_{j3}	Ri_{j3}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_4	P_{j4}	Tec_{j4}	Teh_{j4}	Ti_{j4}	Rec_{j4}	Reh_{j4}	Ri_{j4}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_5	P_{j5}	Tec_{j5}	Teh_{j5}	Ti_{j5}	Rec_{j5}	Reh_{j5}	Ri_{j5}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_6	P_{j6}	Tec_{j6}	Teh_{j6}	Ti_{j6}	Rec_{j6}	Reh_{j6}	Ri_{j6}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_7	P_{j7}	Tec_{j7}	Teh_{j7}	Ti_{j7}	Rec_{j7}	Reh_{j7}	Ri_{j7}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_8	P_{j8}	Tec_{j8}	Teh_{j8}	Ti_{j8}	Rec_{j8}	Reh_{j8}	Ri_{j8}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_9	P_{j9}	Tec_{j9}	Teh_{j9}	Ti_{j9}	Rec_{j9}	Reh_{j9}	Ri_{j9}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_{10}	P_{j10}	Tec_{j10}	Teh_{j10}	Tn_{j10}	Rec_{j10}	Reh_{j10}	Ri_{j10}	A_c/U_n	A_c/U_n	A_c/U_n
				HF_{11}	P_{j11}	Tec_{j11}	Teh_{j11}	Ti_{j11}	Rec_{j11}	Reh_{j11}	Ri_{j11}	A_c/U_n	A_c/U_n	A_c/U_n
				....	...	...	...	...	...	...	...	A_c/U_n	A_c/U_n	A_c/U_n
				HF_i	P_{js}	Tec_{ji}	Teh_{ji}	Ti_{ji}	Rec_{ji}	Reh_{ji}	Ri_{ji}	A_c/U_n	A_c/U_n	A_c/U_n
				...	...	...	...	...	...	...	...	A_c/U_n	A_c/U_n	A_c/U_n
				HF_n	P_{jn}	Tec_{jn}	Teh_{jn}	Ti_{jn}	Rec_{jn}	Reh_{jn}	Ri_{jn}	A_c/U_n	A_c/U_n	A_c/U_n
				Total risk from hazards by type of loss					$\sum Rec_{ji}$	$\sum Reh_{ji}$	$\sum Ri_{ji}$	A_c/U_n	A_c/U_n	A_c/U_n

Table 3

Input data for calculating environmental risk – environmental pollution due to gasoline spillage during pumping from a tanker truck to a storage tank

Specifications	Description
Gasoline type	A92, TLV_{mp}, 5.0 mg/m^3; TLV_{sd}, 1.5 mg/m^3 Hazard class 2
Fuel storage type	Underground location of fuel storage tanks, the technological scheme is characterized by the placement of fuel dispensers above the fuel storage unit, designed as a single factory-made product
Placement	Near the entrance/exit to the settlement of Yuvileinyi in the communal and warehouse zone
Transportation of oil products	Transportation by road
Oil products reception	It occurs through the drain filter by self-flow in the presence of the gas station operator, who controls the tightness of the drain equipment
Control	Presence of sensors for monitoring the level of oil products by filling indicators on tanks
Climate	Temperate: the average daily temperature ranges from – 3 °C in winter to 40.9 °C in summer; wind speed ranges from 6 to 24 m/s, predominantly from the south
Availability of protective equipment	Construction of concrete base for underground tanks and their complete waterproofing; coating of pipelines and tanks with reinforced waterproofing

mental pollution. The proposed risk management process, which takes into account complex hazardous events at technogenic facilities, is aimed at reducing the possibility of implementing technogenic threats. The risk management process is based on the "Bow-Tie" model, which is supplemented with new elements, namely, decomposition of risk into three types of losses: economic, environmental and social, the introduction of secondary hazardous factors (shock waves, debris, toxic gases, etc.) that arise after the primary event, the development of severity scale of consequences with financial thresholds. Moreover, this provides for the possibility to determine the financial thresholds to use existing tools to model the development of hazardous events. To solve a specific problem – calculating the risk of a technogenic accident occurrence at gas stations – it is proposed to use the ALOHA software package to model the affected zones.

In classical risk management methods, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) [6], the main focus is on modelling the sequence of events and assessing the probability of scenarios developing. These methods enable the causes of dangerous situations to be identified and the overall consequences to be assessed. However, they do not take into account that one primary hazardous event can generate multiple secondary factors, each of which has its own consequences. This limits the accuracy of risk assessment, as the cumulative effect of secondary events is not taken into account.

Failure Mode and Effects Analysis (FMEA) methods [16] are focused on process analysis and identification of potential failures. It is effective for systematic analysis of technical systems, but does not take into account the complexity of hazardous events that can have multi-vector consequences. In particular, this method does not allow for the assessment of interactions between different types of losses occurring simultaneously – for example, infrastructure destruction, environmental pollution, and threats to human life.

The Bow-Tie Analysis method [10], used in the proposed work, is a popular tool for visualizing cause-and-effect relationships. In the classic version, it allows threats, barriers and consequences to be identified, but does not provide a quantitative assessment of losses from each individual secondary factor. In the improved version proposed by the authors, the Bow-Tie model is supplemented with a decomposition of risk into three types of losses – economic, environmental and social – which significantly expands its functionality.

The most critical source of risk at gas stations is a violation of the tightness of the tanker truck transporting fuel. In the event of an explosion-hazardous concentration of gasoline vapours in the air and the presence of a source of ignition, an explosion may occur. The size of the affected zone depends on the volume of spilled fuel, which determines the mass of the explosion-hazardous mixture. An explosion occurring above the spill surface has a significantly greater destructive potential than an explosion inside a tanker truck and can cause large-scale consequences, including infrastructure destruction and threat to human life [17].

Given this, investing in the analysis of the potential consequences of such accidents and the implementation of precautionary measures is economically feasible. The costs of preventing emergencies, including planning and technical equipment, are significantly lower than the costs of dealing with the consequences and restoring damaged facilities. Thus, a proactive risk management strategy demonstrates high efficiency in terms of financial investments [18].

It is worth noting the peculiarity of integrating environmental risks specified in the ISO 14001:2015 standard. It turns out that it requires organizations to comply with rules on ensuring environmentally friendly technologies by reducing pollution and supporting investment in sustainable projects [19]. Hence, there is a need to identify stakeholder support through a developed toolkit to en-

Table 4

Example of identifying the fuel explosion hazard at a gas station

Hazard No.	Identification				Primary analysis – determining the risk level for each HF and the risk, as well as assessing the risk in terms of economic, environmental ones, loss of life and health of employees									
	Hazard	Hazardous event	Negative consequences of economic and environmental losses, as well as loss of human life and health	Influence on the probability of a hazardous event occurring and/or on the severity of the hazardous event consequences	Probability of a hazardous event occurring from HF for each negative consequence	The degree of severity from the hazardous event occurring for each HF for each negative consequence			The risk level of a hazardous event occurring for each HF for each negative consequence			Hazard risk assessment – *j* for each HF – *i* for each negative consequence		
						Infrastructure destruction	Loss of life and health of personnel	Environmental	Infrastructure destruction	Loss of life and health of personnel	Environmental	Infrastructure destruction	Loss of life and health of personnel	Environmental
j	Fuel	Fuel explosion	Disruption of the normal economic and financial activities of the organization, disruption of life in the ecosystem of trauma, occupational diseases resulting from accidents	Human factor – lack of competent personnel	5	5	4	3	25	20	15	U_n	U_n	A_c
				Technical factor – structural defects of tanks	3	5	4	3	15	12	9	A_c	A_c	A_c
				Technical factor – malfunction of fuel drain control systems	3	5	4	3	15	12	9	A_c	A_c	A_c
				Technical factor – malfunction of safety valves, fire safety devices	3	5	4	3	15	12	9	A_c	A_c	A_c
				Organizational factor – lack of control over the reporting on measures taken	3	5	3	3	15	9	9	A_c	A_c	A_c
				Total risk from hazards by type of loss					91	93	83	U_n	U_n	U_n

sure improvement of overall corporate stability in relation to the development of the organization, specifically in combination with economic and professional hazards, which are often interrelated and even interdependent.

Such hazards include inadequate waste management, uncontrolled energy consumption and emissions of pollutants into water, atmospheric air and soil, risks related to improving technological processes and reducing environmental risks, which are also characteristic of economic inconsistencies, as hazardous factors that increase the probability of economic losses of the company [20].

As a result, the proposed risk management process contributes to greater coordination of actions between the structural units of the organization, which forms a synergistic effect: the overall result of joint work exceeds the sum of individual achievements.

This provides a number of strategic advantages:

1. Increased competitiveness by improving the reputation and management process efficiency.

2. Overcoming the fragmentation between units that often occurs when implementing separate management systems.

3. Resource rationalization – an integrated system is easier to maintain and administer than several independent ones.

4. Ensuring transparency — reducing the number of internal and external links contributes to better manageability.

5. Document flow optimization – reduction in documentation volume through system unification.

6. Reducing conflicts between economic, environmental and safety aspects, enabling a holistic approach to management.

7. Improving the efficiency of resource use and improving the coordination of information flows.

8. Strengthening environmental and technogenic safety in areas where organizations operate.

The implementation of the above results will ensure the sustainable development of the organization. This will not only provide competitive advantages in the future, but will also help to minimize losses through appropriate risk management processes, taking into account economic and environmental losses resulting from their consequences, given that the greatest economic (financial) burden on organizations is caused by increasing environmental standards. Limiting financial resources requires redistributing funding and determining safe operation limits for the organization, as well as the implementing appropriate changes in business processes. This encourages organizations to seek sustainability limits that will allow them to balance challenges (hazards) and the losses that the organization will incur to eliminate them.

Conclusions.

1. The model of cause-and-effect relationships between the occurrence of a primary hazardous event and the severity of the consequences from each secondary hazardous event generated by the primary hazardous event has been improved, allowing the risk to be determined taking into account losses from infrastructure destruction, human life and health losses, and environmental losses. The proposed model clearly distinguishes between the primary hazardous event and multiple secondary hazardous factors (such as shock wave, thermal radiation, toxic dispersion) that are their source.

2. A risk management process has been developed for the safety management system of technogenic facilities, consisting of eight steps, which differs from the known ones by defining the risk of losses from each secondary hazard in the form of the manifestation of corresponding hazardous factors that arise as a result of the occurrence of a hazardous event. This requires a separate quantitative assessment for each secondary hazardous factor across three different vectors of consequences (infrastructure, environmental, human). Such an approach provides a comprehensive assessment, preventing underestimation of the total risk by systematically taking into account all factors and their various impacts.

3. A severity scale of hazardous event consequences is proposed, based on determining the damage caused to the sustainable functioning of a particular facility infrastructure, taking into account the costs of localization and liquidation of the accident, environmental damage due to pollution of the atmosphere, surface waters, soil and resources (in particular, land, water, wildlife or protected flora and fauna, forest fund or vegetation), as well as human life and health.

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Розробка підходу з керування ризиками в системі безпеки техногенних об'єктів

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Мета. Полягає у розробці процесу керування ризиками комплексних небезпечних подій у системах управління безпекою техногенних об'єктів.

Методика. Для розробки процесу керування ризиками, обумовленими комплексом небезпечних подій, за основу взято найбільш поширену модель «краватка-метелик», що дозволяє встановити причинно-наслідковий зв'язок між небезпекою, небезпечною подією й тяжкістю наслідків.

Результати. Удосконалена модель причинно-наслідкових зав'язків між настанням первинної небезпечної події та тяжкістю наслідків від кожної вторинної небезпечної події, що породила первинна небезпечна подія. Розроблено процес керування ризиками в системі управління безпекою техногенних об'єктів, що складається із восьми кроків, який відрізняється від відомих визначенням ризику втрат від кожної вторинної небезпеки у вигляді відповідних небезпечних чинників, що з'являються в результаті настання небезпечної події. Запропоновано для визначення шкали тяжкості наслідків встановити збитки, що заподіяні сталому функціонуванню інфраструктури певного об'єкту з урахуванням витрат на локалізацію й ліквідацію аварії та екологічною шкодою.

Наукова новизна. Полягає у розробці процесу керування ризиками, з урахуванням комплексних небезпечних подій у системах управління безпекою техногенних об'єктів, в якому, на відміну від існуючих, проводиться оцінювання тяжкості наслідків первинної небезпечної події.

Практична значимість. Полягає у розробці процесу керування ризиками небезпеки та втрат у системі управління безпекою, спричиненими комплексом небезпечних подій, що відрізняється від відомих додатковим визначенням втрат, обумовлених вторинними небезпеками.

Ключові слова: *техногенні об'єкти, ризик, небезпечна подія, управління безпекою*

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