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Risk Assessment of Man-Made Emergencies at Chemically Hazardous Sites in a Phosphate Fertilizer Production Facility

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ABSTRACT

The aim of the study is to validate a novel methodology for assessing the risk of man-made emergencies at chemically hazardous sites (CHSs) of a phosphorus fertilizer manufacturing enterprise. Two independent indices were used to assess the state of the occupational health and safety management system: accident risk levels and occupational injury rates. The assessment of accident risk is based on expert evaluation, while the assessment of occupational injury risk is based on statistical methods. It was established that at the CHSs under study, the main parameters determining accident risk are technological and auxiliary equipment, the corrosive activity of the chemically hazardous substances used, and the lack of effective methods for identifying, assessing, and controlling the hazards of technological processes. Fatal accidents occurring in various departments indicate a critical level of occupational injury risk at the enterprise. The application of the methodology used in the article in the practice of occupational safety specialists at enterprises with a CHS and supervisory organizations in the field of industrial safety and emergency situations will allow monitoring the functioning of the enterprise's occupational safety management system and evaluating the effectiveness of corrective measures.

1. INTRODUCTION

Phosphate fertilizers are the cheapest and simplest means of increasing the yield of agricultural crops. In the Republic of Kazakhstan, phosphorus fertilizer production in the first half of 2024 increased by 60% year-on-year and reached 14.6 thousand tones. At the same time, the share of phosphorus fertilizers produced by Kazakh manufacturers in the local market was 99.5% [1].

The technological process of phosphorus fertilizer production involves the use of hazardous chemicals (HCs) at various stages of production. Disruption of technological processes at chemically hazardous sites (CHSs) can lead to major accidents with serious undesirable consequences for people, enterprises, and the environment [2-5]. This requires special attention to industrial safety issues at chemical fertilizer production facilities, because statistics show a steady increase in accidents resulting in casualties among personnel and environmental pollution.

On 19 February 2025, an ammonia leak occurred at the Apatit JSC (PhosAgro Group) plant in Balakovo, Saratov Region (Russian Federation), resulting in the death of one worker and the hospitalization of another with acute poisoning [6]. Later, on 3 April 2025, a local leak occurred at the same enterprise at the ammonia evaporation unit, resulting in the intoxication of five workers [7]. On 11 July 2022, at the sulphuric acid workshop of the Mineral Fertilizers enterprise, a branch of the Kazphosphate company in Taraz (Republic of Kazakhstan), a malfunction of the monohydrate pump of the second stage purification absorber led to a short-term release of waste gas - sulphur trioxide [8]. Measurements taken at one of the points in the plant's sanitary protection zone revealed a significant excess of hydrogen fluoride in air samples [9]. Earlier, on 1 July 2022, two employees of the same enterprise died after falling into the grinding machine [8]. Such frequent accidents at enterprises with CHSs indicate serious gaps in the functioning of their occupational safety management systems and require the immediate development of effective preventive measures.

One such measure is risk assessment, which identifies weaknesses in manufacture organization, technology, personnel functioning, and industrial equipment. The probability and severity of accidents can be reduced through appropriate risk management processes [10, 11]. As stated in ISO 31000: 2018, the risk management process "... involves the systematic application of policies, procedures and practices to communication and consultation activities, context establishment and risk assessment, treatment, monitoring, review, recording and reporting" [12].

With this in mind, Rausand and Haugen [13] identified the following aims of the risk management process:

(1) identification, analysis and assessment of potential hazards in the occupational health and safety management system and technological processes;
(2) definition and implementation of control measures to eliminate or reduce potential risks to people, assets or the environment.

This process consists of four main stages, that is, risk assessment, risk treatment, risk communication, and risk monitoring and review. In particular, the risk assessment stage is fundamental to preventing accidents and mitigating their consequences [14, 15]. According to the classic "triple definition of risk" formulated by Kaplan and Garrick [16], risk can be expressed in terms of what can go wrong (scenario), the probability of it happening (probability), and the severity of the consequences (consequence). Thus, "risk assessment" should also be understood to mean methods for identifying hazards and accident scenarios, analyzing probabilities and consequences, and considering this term from a synecdochical point of view [2, 17].

A wide range of risk assessment methods are used worldwide, with varying degrees of applicability in chemical industry enterprises. The most well-known are hazard and operability analysis (HAZOP), failure mode and effects analysis (FMEA), and layer of protection analysis (LOPA) [18].

HAZOP is a fairly reliable qualitative method that effectively identifies hazards in chemical processing. At the same time, it is very labor-intensive, does not provide a quantitative risk assessment, and does not determine whether a risk is acceptable. The LOPA method, being semi-quantitative, has certain fundamental limitations that make it difficult to apply in the risk analysis of chemical accidents. For example, the simplified model of reality does not allow for a full consideration of the role of human and organizational factors. Additionally, chemical production is considered in a steady-state condition, without accounting for equipment wear and the accumulation of latent defects. The main drawbacks of FMEA that hinder its use in assessing accident risks at chemical plants are the inability to perform a true quantitative risk assessment, as well as its labor-intensive and cumbersome nature. This method does not analyze the effectiveness of safeguards, as it is largely focused on failures.

However, recently, researchers have been paying a lot of attention to the systems theory model of accidents and processes (STAMP) [19, 20]. STAMP helps to analyze how various (mostly technical and organizational) factors interact with each other. This methodology focuses on complex interactions and relationships within the system, based on the principles of control systems and equilibrium theory, which allows the creation of a safety management structure for studying the system as a whole and analyzing its emergent properties.

At the same time, applying STAMP principles to the analysis of risks associated with the operation of CHS requires a detailed and resource-intensive data collection process, both in terms of document analysis and verification by experts in the field [21]. A common feature of the aforementioned methods that makes their application in Kazakhstan difficult is the use of statistical data on accidents and failures. The need for statistical data on accidents at CHS (in the absence of a database in the Republic of Kazakhstan) [22], the problematic nature of developing automated information systems based on the above-mentioned methodologies, as well as their considerable labor intensity, requiring a high professional level of risk assessment specialists, are serious obstacles to their widespread application both in enterprises and by supervisory authorities. This makes it urgent to search for new methodological approaches that are objective, universal and relatively simple in terms of methodology. The aim of this article is to present one such approach and evaluate its effectiveness using the example of a phosphorus fertilizer production enterprise.

Unlike the methods described above, the method used here takes into account the physicochemical properties of HCs that could influence the development of an emergency (in particular, corrosive activity and fire and explosion hazards). The method used is aimed at assessing the current situation at a facility with CHSs, primarily from the perspective of preventing the occurrence (forecasting) and further development of an emergency, rather than analyzing the consequences of undesirable events. The previously presented methodology was tested at chemical production facilities manufacturing nitrogen fertilizers [17], sulfuric acid [19], and chlorine [20]. The methodology has significant potential for application, as it accounts for the process equipment used in various technological processes for the synthesis of a wide range of chemical products.

2. METHODOLOGY

The lack of a unified database on accidents at CHS in Kazakhstan significantly hinders the use or development of new posteriori risk assessment methods. In this regard, the most promising approach is to develop a multi-criteria methodology for assessing accident risk based on expert evaluation. At the same time, the amount of available information on work-related injuries allows it to be used effectively for statistical analysis.

According to the presented methodology, the assessment of the risk of man-made accidents at the CHS includes the following stages: preliminary research, collection and formation of a database of initial data, and accident risk level assessment. Figure 1 illustrates the sequence of steps in the developed methodology. In the first stage, an expert group is formed to identify clusters of criteria parameters and determine their weights for calculating the hazard index of the CHS and the vulnerability of the staff working there. The result of this stage is a set of questionnaires that are completed by researchers during the study of the CHS in the second stage. In the third stage, calculations are performed to determine the risk level at the CHS, the enterprise as a whole, and the accident hazard class of the CHS.

The overall safety level of an industrial enterprise is assessed based on two independent indicators: the risk of accidents and the risk of work-related injuries in specific departments (sections) of the enterprise. The expert assessment method was used to determine the accident risk level. An expert group was formed, consisting of:

(1) employees of the Industrial Safety Committee of the Ministry of Emergency Situations of the Republic of Kazakhstan – 6 people;
(2) employees of the Emergency Prevention Committee of

the Ministry of Emergency Situations of the Republic of Kazakhstan – 5 people;

(3) employees of the Industrial Safety Department of the Ministry of Emergency Situations of the Republic of Kazakhstan for the Karaganda Region – 6 people;

(4) employees of enterprises with chemically hazardous sites responsible for their safe operation – 9 people.

The average experience of the experts was 12.5 years.

The expert evaluation was carried out in two stages. In the first stage, using literature sources, criteria parameters that influence the accident rate in technological processes were selected. In the second stage, experts added (or revised) the criteria parameters based on the specific characteristics of the industrial processes and determined their weighting in the risk assessment. The results were processed by simply averaging the expert consensus.

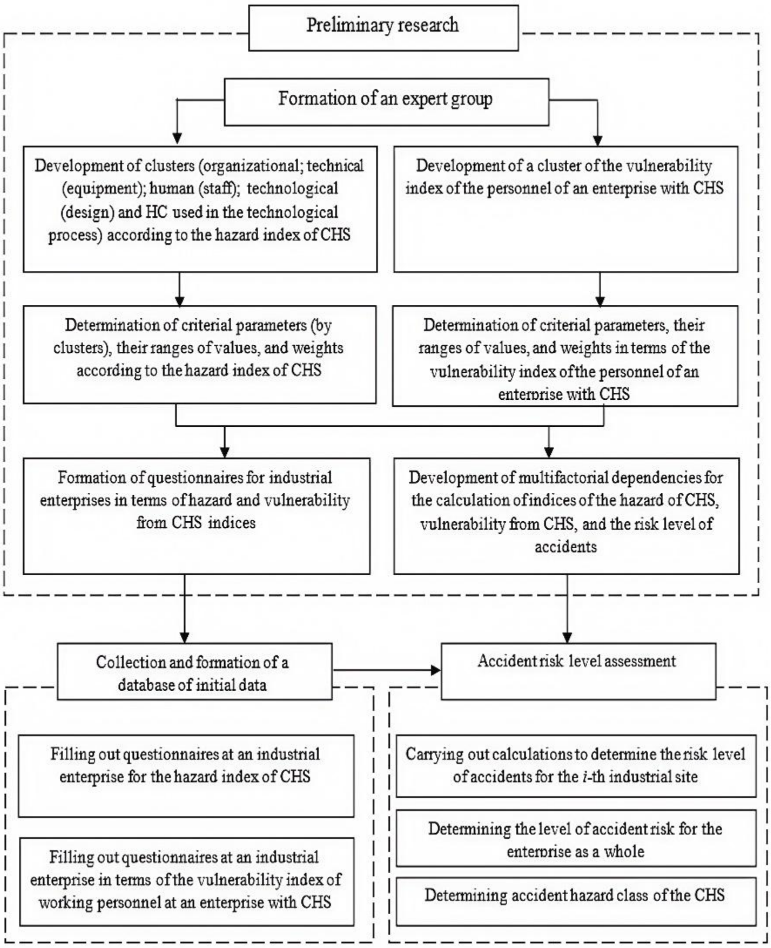

Figure 1. Workflow of the proposed risk assessment methodology

A previously published article [23] provides detailed information on the methodology for forming the expert group.

The accident risk level at the CHS was determined based on the ratio of the CHS hazard index (HI) to the vulnerability of the enterprise's personnel to the CHS index (VI). The HI was calculated based on the values of indices included in the organizational, technical, human, and technological criteria clusters, taking into account the weight of each cluster and index. The VI was calculated based on the values of indices included in the vulnerability cluster, taking into account the weight of each index.

The hazard index for the i-th industrial site of the enterprise is defined as the sum of the criteria parameters associated with the four clusters, weighted by their respective coefficients (1).

$$HI_i = \sum_{m=1}^{4} w_m \cdot C_m$$

where, m is the number of clusters (m = 1…4), and C is a quantitative measure of the criteria parameters included in the respective cluster.

The vulnerability index of staff who may be exposed to a damaging effect is determined based on the degree of influence of a set of criterial parameters $\{m\}$ and the significance of their values:

$$VI_i = \sum_{j=1}^{m} a_j \cdot y_j$$

where, a_j denotes the weight of the j-th vulnerability descriptor; y_j denotes the score of the vulnerability descriptor; m is the number of descriptors forming a cluster for estimating the vulnerability index of the operating staff.

The level of risk of work-related injuries was determined using a matrix based on the ratio of injury frequency and severity indices among workers at the studied industrial sites. These indices were calculated based on statistical data obtained from the occupational safety department of the enterprise under study.

The assessment allows the accident and injury risk class to be established for both individual structural divisions and the enterprise as a whole. An original patented methodology was used to assess the risk of man-made emergencies at the enterprise under study. This methodology was described in more detail in a previously published article [24].

3. RESULTS AND DISCUSSION

3.1 Results

The main activity of the enterprise under research is the production of mineral (phosphorus-nitrogen) fertilizers and feed phosphates. The sulphuric acid which is necessary for their production is also produced at this enterprise. There are three CHSs located on the territory of the enterprise: a contact sulphuric acid workshop (sulphuric acid is in circulation), an ammophos production workshop (ammonia, sulphuric and orthophosphoric acids) and a feed-grade defluorinated phosphate production workshop (hydrogen fluoride). In Tables 1–8 below, the data for these CHSs correspond to columns 1, 2, and 3.

Liquid sulphur produced by melting is burned in three cyclone furnaces in the sulphuric acid production workshop. The raw material for the manufacture of sulphuric acid used in the production of ammophos is sulphuric acid produced from technical lump sulphur. Sulphuric acid is prepared by saturating the sulphurous anhydride formed during the combustion of sulphur with water.

The main raw materials for the manufacture of ammonium phosphates in the ammophos workshop are orthophosphoric acid and ammonia. Orthophosphoric acid is neutralized in a reactor using ammonia. The resulting product is then granulated and dried.

The technology for producing defluorinated phosphates for animal feed by hydrothermal processing of natural phosphorites in a melting cyclone according to an energy technology scheme is based on the following principle. The heat released by the combustion products is used in the unit to generate steam with the required energy parameters. The energy technology unit contains a melting unit (a cyclone furnace with a melt collector), a radiation chamber, a steam superheater, an air preheater, an economizer, and operates on natural circulation.

3.1.1 Calculation of accident risk and determination of the accident hazard class of chemically hazardous sites and enterprises as a whole

Table 1 shows the scores for the criteria parameters that make up the organizational cluster. The criteria parameters of the organizational cluster are described in the same order for all the occupational health and safety CHSs studied, as the enterprise has a centralized occupational health and safety service.

Table 1. Scores for the criterial parameters included in the organizational cluster

Name of Criterion Parameter	Weight	CHS, Score		
		1	2	3
Organization of training in industrial safety management	0.047	1	1	1
Functioning of the department (person in charge) for industrial safety and occupational health at the enterprise	0.034	2	2	2
Availability of a complete set of technical documentation, reports, logs, passports	0.015	1	1	1
Periodic review of instructions and schemes	0.015	3	3	3
Completing written work procedures and tasks with clear instructions	0.065	1	1	1
Conducting a process hazard analysis (PHA) to identify, evaluate and control PHA	0.068	4	4	4
Application and verification of the condition of control and measuring instruments (CMI) and automation equipment	0.021	1	1	1
Periodic inspections of workplaces, equipment, and construction in accordance with design specifications and safety requirements	0.047	1	1	1
Monitoring the condition of the enterprise territory (site) in proper order (accident-free condition)	0.020	1	1	1
The staff's ability to provide feedback to management on process risk analysis and other process management elements. The availability of safety incentive programmes	0.056	1	1	1
Availability of a detailed emergency action plan. Conducting training and training exercises	0.010	1	1	1
Periodic audit of industrial safety management	0.007	1	1	1
Maintaining auxiliary systems in proper working order: ventilation, heating, sewerage at the enterprise as a whole, in sites, and workplaces	0.025	3	3	3

A survey of personnel at the CHSs under study made it possible to determine the necessary parameters for the industrial safety management system. All personnel underwent timely training in the course "Industrial Safety at Hazardous Industrial Sites." The workshops under study have complete documentation regulating the frequency of inspections and repairs of equipment and control and measuring instruments and devices, and confirming that these have been carried out. All written work procedures and tasks in the workshops under study are implemented in full. The facilities are fully equipped with the necessary control and measuring instruments and automation equipment. Regular inspections are carried out in the workshops in accordance with the plan to ensure that workplaces, technological equipment, and protective devices comply with industrial safety requirements. The company constantly encourages staff feedback on compliance with industrial safety requirements, which is encouraged by the administration: staff suggestions are recorded in a control log, and an "Ideas Factory" project has been launched, aimed, among other things, at improving the safety of industrial processes in the workshops.

The enterprise has a health and safety department, whose employees are assigned to specific workshops and rotate annually. The department has a staff of 8 people, with plans to expand to 12. The employees responsible for the workshops under study have 3-5 years of experience. In all workshops, instructions and diagrams aimed at ensuring the safety of technological processes (every 3 years) and technical regulations (every 5 years) are reviewed in a timely manner. To analyze process hazards (PHA) in the workshops under survey, employees use a hazard and risk register at the beginning of each shift. The company continuously and effectively (100%) monitors the condition of the territory in an appropriate manner. All workshops have a detailed emergency response plan for personnel, and training sessions on emergency response are conducted regularly. The access, parking, and exit areas for special equipment used for emergency response, in accordance with the emergency response plan, are in good condition. Internal and external industrial safety management audits are carried out annually in the workshops under review. The ventilation, heating, and sewage systems at the enterprise as a whole and in its individual divisions are maintained in satisfactory condition.

As shown by the analysis of the criteria parameters included in the organizational cluster, most of them have minimal significance. It is recommended that the responsible persons at the enterprise implement advanced process hazard analysis methods for more effective identification, assessment, and control of PHA, and modernize the ventilation systems in the workshops under study. Table 2 presents the criteria parameters characterizing the technological equipment and its condition, as well as safety and localization measures in the workshops under study.

Table 2. Scores for the criterial parameters included in the technical cluster

Name of Criterion Parameter	Weight	CHS, Score		
		1	2	3
Pressurized vessels, group	0.023	4	2	3
Separation equipment	0.014	4	4	2
Chemical reactors. Operating volume	0.011	5	5	0
Heat exchange equipment. Heating surface square	0.011	5	2	0
Length of pipeline systems transporting hazardous chemicals	0.046	5	5	2
Wear coefficient of fixed assets	0.035	5	5	5
Replacement coefficient of fixed assets	0.025	5	4	5
Capacity of pumps (compressors)	0.020	5	5	5
Number of storage tanks for HCs at the site	0.029	3	5	0
Controls (control devices, alarms, sensors, interlocks, availability of safety systems, including automatic shut-off valves)	0.026	1	1	1
Availability of means of localization	0.010	1	1	1

Note: hazardous chemicals = HCs; chemically hazardous sites = CHSs

The sulphuric acid workshop uses pressurized vessels belonging to group 2. The separation equipment used has a volume of approximately 100 m³. The same workshop uses two chemical reactors – a furnace boiler and a start-up boiler, each with a volume of 50 m³. The workshop uses shell-and-tube heat exchangers with a total heating surface area of over 1,000 m³. The total length of pipes used for sulphuric acid transportation is 200 m, while that for sulphurous anhydride is 150 m. The wear coefficient of fixed assets is 50%, and the replacement coefficient is 20%. The capacity of the three air supply compressors is 120,000 m^3/h. Outside the workshop, there are three tanks with finished sulphuric acid, each with a volume of 1,200 m^3. The technological equipment is equipped with all necessary control devices, localization means, emergency discharge and ventilation systems and devices.

The ammonium phosphate workshop uses pressurized vessels belonging to group 4. The ammonium phosphate workshop uses explosion-proof separation equipment with a volume of 60 m³. A decomposition reactor (650 m^3) and a maturation reactor (450 m^3) are used for the decomposition reaction – mixing of phosphorite with sulphuric acid. Ten bubblers are used for bubbling, with a total heating surface area of 200 m^2. The length of the pipeline systems transporting sulphuric acid is 2,000 m, and ammonia – 1,650 m. The wear coefficient of fixed assets is 30%. The replacement rate of fixed assets is 50%. The capacity of each of the four air supply compressors is 300 m^3/h. The ammonium phosphate workshop also has three pumps with a capacity of 800 m^3/h each. The workshop has 20 ammonia tanks with a capacity of 100 m³ each, 11 sulphuric acid tanks with a capacity of 2,000 m³ each, four tanks with a capacity of 450 m³ and two tanks with a capacity of 200 m³ containing orthophosphoric acid. The process equipment is equipped with all necessary controls, localization devices, emergency discharge, and ventilation systems and devices.

The workshop for the production of defluorinated feed phosphates uses pressurized vessels belonging to group 3. The workshop uses two separators, each with a volume of 4 m^3. No chemical reactors or heat exchange equipment are used in the workshop. The length of the piping systems transporting hydrogen fluoride is 60-70 m. The depreciation rate of fixed assets is 100%, and the replacement rate of fixed assets is 0%, as the equipment is not being upgraded, but its service life is being extended. The compressors have a capacity of 40,000 m^3/h. There are no tanks for storing HCs in the workshop. The process equipment is equipped with all the necessary controls, localization devices, emergency release, and ventilation systems and devices.

The scores for the criteria parameters in the technical cluster presented in Table 2 are quite high. Many of these criteria parameters require permanent monitoring, as they describe equipment that cannot be changed. Attention should be paid to criteria parameters 6 and 7, which indicate significant wear on the equipment used and the need to carry out work to upgrade fixed assets and funds.

Surveying the workshops under study made it possible to determine the necessary indicators characterizing the contribution of their personnel to the possible development of an accident situation (Table 3). In all three workshops, depending on the specifics of the technological process, the personnel work in two shifts. All personnel of the sulphuric acid workshop underwent timely training and successfully passed an exam on knowledge of safety regulations and industrial safety at hazardous industrial sites. At the same time, compliance with safety regulations and the production process among contractors was 60%. The workshop teams are 90% staffed.

All personnel in the ammonium phosphate workshop underwent timely training and successfully passed an exam on safety regulations and industrial safety at hazardous production facilities. At the same time, compliance with safety regulations and industrial processes among contractors was 90%. The workshop teams are 95% staffed.

All personnel at the workshop for the production of defluorinated feed phosphates have undergone timely training and successfully passed an examination on safety regulations and industrial safety at hazardous industrial sites. No contractors are employed at this workshop. The workshop teams are 85% staffed.

As shown by the analysis of the criteria parameters of the cluster describing the staff working at an enterprise (Table 3), the enterprise's occupational health and safety service should pay particular attention to the knowledge level of safety techniques and the industrial process among contractors.

Table 3. Scores for the criterial parameters included in the human (staff) cluster

Name of Criterion Parameter	Weight	CHS, Score		
		1	2	3
Assessment of staff knowledge of occupational health and safety and operational instructions, the dangers of HCs in circulation, and manufacturing process technology. Number of CHS's workers who have completed the course "Industrial Safety at Hazardous Industrial Sites" / advanced training (for the reporting period)	0.034	1	1	1
Compliance of contractors' knowledge of safety techniques and manufacturing processes (similar to point 1)	0.010	5	3	0
Team staffing level	0.031	2	1	3
Work process schedule	0.015	3	3	3

Note: hazardous chemicals = HCs; chemically hazardous sites = CHSs

Table 4. Scores for the criterial parameters included in the technological (design) cluster

Name of Criterion Parameter	Weight	CHS, Score		
		1	2	3
Functioning of the Change Process Management System	0.038	5	5	1
Compliance with the design solutions of buildings and constructions, warehouses, places of storage of hazardous chemicals	0.023	1	1	1
Compliance with the design solutions of protective and safety devices, control equipment	0.016	1	1	5
Compliance with the design of ventilation, heating, sewerage, plumbing, lighting systems at workplaces, sites, the enterprise as a whole	0.017	1	1	1
Compliance with the design of the operation of processing lines and new equipment	0.021	1	1	1
Data on corrosivity	0.013	5	5	1
Storage volume	0.024	5	5	0
Hazard classes of chemical products, which are: -flammable liquid -flammable solid -flammable gas	0.015	0	0	0
Hazard classes of explosive chemical products	0.020	0	0	0
Temperature class (Autoignition temperature of the mixture)	0.010	1	1	1
Combustibility group	0.013	0	0	0

Note: chemically hazardous sites = CHSs

Table 4 shows the technological criteria for the industrial safety management system assessment at the studied CHSs, including the properties of HCs that affect the safety of technological processes. All workshops have a change management system in place: changes are considered annually with the aim of improving occupational safety. Buildings, constructions, warehouses for storing HCs, the operation of technological lines and new equipment, protective and safety devices, instrumentation, ventilation, heating, water supply, sewage and lighting systems fully comply with the design solutions. The ammonia production workshop warehouse can store up to 2,079 t of liquid ammonia, the weak nitric acid workshop can store up to 250 t of nitric acid, and the complex mineral fertilizer production workshop does not store HCs. As can be seen from Table 4, the criterion parameter "Storage volume" in the first two workshops has a maximum value of 5 points, which indicates the need for careful monitoring of the condition of the CHS tanks.

There is no change management system in the contact sulphuric acid and ammonium phosphate production workshops. In these workshops, the buildings, constructions, warehouses for storing HCs, the operation of process lines and new equipment, protective and safety devices, instrumentation, ventilation, heating, water supply, sewerage and lighting systems are fully compliant with the design solutions. The contact sulphuric acid workshop has tanks that store 6,000 t of sulphuric acid.

The ammonium phosphate production workshop has tanks storing 1,000 tonnes of ammonia, 300 t of orthophosphoric acid and 20,000 t of sulphuric acid. Table 4 shows the maximum scores corresponding to the properties of the HCs stored in this workshop.

The feed defluorinated phosphate production workshop has a change management system in place. Buildings, constructions, warehouses for storing HCs, the operation of production lines and new equipment, ventilation, heating, water supply, sewerage and illumination systems are fully compliant with the design specifications. 50% of the protective and safety devices and instrumentation and control equipment in the workshop have been modernized. There are no chemical storage tanks on the workshop premises; hydrogen fluoride circulates in the workshop exclusively through pipelines.

As can be seen from Table 4, the criterion parameter "Storage volume" in the first two workshops has a maximum value of 5 points. At the same time, the sulfuric acid present in the workshops is highly corrosive. Although, according to experts [24], the criteria parameters "Storage Volume" and "Corrosive Activity" do not have the highest weighting coefficients in the cluster, this indicates the need for careful monitoring of the condition of tanks containing HCs.

Table 5 presents the values of parameters characterizing the vulnerability of personnel at the researched CHSs.

In all of the workshops studied, in the case of an accident involving HCs, all personnel will have enough time to evacuate from the emergency area. There is a personnel evacuation plan in place for emergencies, and the industrial premises have at least two emergency exits. In all three workshops under study, the technological equipment is equipped with safety devices, and all workplaces are equipped with local ventilation, water supply, sewerage, and protective devices.

No protective structures are required in the contact sulphuric acid and defluorinated feed phosphate workshops. In these workshops, auxiliary safety equipment is 100% complete. Dust suppression, aspiration, ventilation, disposal, and localization systems for pollutants are maintained in excellent condition. All equipment is 100% equipped with the necessary remote control and monitoring systems, a self-start protection system, and round-the-clock surveillance.

The personnel of these workshops are fully equipped with the necessary personal protective equipment (PPE). PPE at workplaces is in excellent condition.

The effectiveness of protective structures in the ammonium phosphate production workshop is over 80%. In the same workshop, the availability of auxiliary safety equipment is over 80%. Aspiration, ventilation, dust suppression, disposal and localization systems for pollutants are maintained in good condition. Given the specific nature of the technological process, more than 80% of the equipment is equipped with the necessary remote control and monitoring systems, a self-start protection system, and round-the-clock surveillance. More than 80% of the workshop staff are equipped with the necessary PPE. PPE at workplaces is in good condition.

The values of the cluster criteria parameters for assessing the vulnerability of operating personnel (Table 5) in the contact sulphuric acid and defluorinated feed phosphate workshops are minimal. This indicates that sufficient measures are being taken in the workshops under study to improve the safety of operating personnel. In the ammophos production workshop, some shortcomings were noted in the provision of collective and PPE and their technical condition, which requires their modernization.

Table 5. Scores for the criterial parameters included in the cluster for assessing the vulnerability of staff when exposed to destructive factors as a result of man-made emergencies

Name of Criterion Parameter	Weight	CHS, Score		
		1	2	3
Availability of time for evacuation and other emergency measures in the case of an accident	0.40	1	1	1
Availability of a plan for the evacuation of personnel of the CHS in the case of equipment failure or an emergency and the presence of evacuation exits in the premises of the engine room and hard wareroom	0.10	1	2	1
Presence of protective structures	0.10	1	2	1
Presence of identification marks, fences, light signaling, removable lockable shields, warning alarms, warning posters	0.03	1	2	1
Presence of systems of aspiration, ventilation, dust suppression, disposal and localization of harmful substances	0.07	1	2	1
Presence of remote devices and controls, control systems, providing protection against self-starting, round-the-clock surveillance	0.05	1	2	1
Presence of protectors	0.05	1	1	1
Presence of local ventilation systems, local suction systems, individual sewerage, water supply and protective devices	0.09	1	1	1
State of personal protective equipment	0.05	1	2	1
Staffing of the enterprise personnel with personal protective equipment	0.06	1	1	1

Note: chemically hazardous sites = CHSs

Table 6. Accident modelling results

Indices	CHS, Score		
	1	2	3
Hazard index	2.412	2.408	1.678
Vulnerability index	1.0	1.4	1.0
Accident risk level	Small	Small	Insignificant
Accident hazard class	IV	IV	V

Note: chemically hazardous sites = CHSs

The accident risks and accident classes of the chemically hazardous sites under study were determined using a matrix [24]. Table 6 presents the results of accident modelling at the workshops under study. As can be seen from the results of the accident risk assessment at the CHS under study, for the contact sulphuric acid and ammophos workshops, it is assessed as "low" and assigned accident hazard class IV, while for the defluorinated feed phosphate workshop, it is assessed as "insignificant" accident risk and assigned accident hazard class V. For the enterprise as a whole, the accident risk is defined as "small" and assigned accident hazard class IV.

3.1.2 Calculation of the risk of work-related injuries and determination of the injury hazard class of chemically hazardous sites and the enterprise as a whole

The average number of employees in the sulfuric acid workshop for the period under study was 110 people (Table 7). Over the past 5 years, there has been 1 fatal accident in the workshop.

Table 7. Scores for the indicators included in the cluster for assessing the risk of work-related injuries

Indicators	CHS, Score		
	1	2	3
Number of accidents at the enterprise (in its individual divisions) during the study period	1	4	0
Average number of employees at the manufacturing enterprise (in its individual divisions) during the study period	110	450	135
The degree of permanent workers' workability loss as a result of injuries sustained during the study period	Fatal	10%, 60%, 50%, fatal	-

Note: chemically hazardous sites = CHSs

Table 8. Results of modeling on work-related injuries

Indicators	CHS, Score		
	1	2	3
Work-related injury frequency coefficient	0.0091	0.009	0
Coefficient of the severity of harm to the health	Fatal	Fatal	-
Risk level of work-related injuries	Critical	Critical	None
Injury hazard class	I	I	V

Note: chemically hazardous sites = CHSs

The average number of employees in the ammophos workshop for the period under study was 760 people. Number of workplaces is 450. Over the last 5 years, 4 accidents have been registered in the workshop:

(1) a pump operator received a minor injury as a result of being hit by a moving part of the process equipment;
(2) a repairman received a serious injury as a result of falling from a height;
(3) a drying operator received a serious injury after falling from a height as a result of exposure to a shock wave;
(4) a fatal accident occurred as a result of a load falling during mining excavation.

The average number of employees in the workshop for the production of feed defluorinated phosphates during the study period was 135 people. Over the past 5 years, no accidents have been recorded in the workshop.

Using the matrices [24], the risks of industrial injuries and injury hazard classes of the studied CHSs were determined. Table 8 presents the results of the conducted modeling of industrial injuries in the studied workshops. As follows from the results of the injury risk assessment at the studied CHSs, it is “critical” in the contact sulfuric acid and ammophos workshops (injury hazard class – I), and it is absent in the feed defluorinated phosphates workshop (injury hazard class – V). For the enterprise as a whole, the risk level and accident hazard class are defined as “critical” (injury hazard class – I).

3.2 Discussion

As the conducted study showed, the use of the original methodology allowed us to objectively assess the risks of man-made emergencies at various CHSs of the enterprise for the production of phosphorus fertilizers. The methodology comprehensively assesses the contribution of organizational and human factors, industrial equipment, means of ensuring the safety of technological processes, properties of HCs and vulnerability of personnel to the probability and severity of the consequences of man-made emergencies. It is worth noting the sufficient consistency between the results of a priori (accident risk) and a posteriori (work-related injury risk) risk assessments. Thus, the low hazard index value in the feed-grade defluorinated phosphate production workshop (Table 6), compared to the other CHSs studied, is combined with the absence of work-related injuries among the workers of this workshop during the study period (Tables 7 and 8).

The accident risk analysis showed that the main risk factors for emergencies at CHSs of the phosphorus fertilizer production enterprise are the process and auxiliary equipment and its technical condition. In addition, the critically high level of work-related injuries at the enterprise indicates that, along with equipment modernization, the enterprise needs to implement effective methods for identifying, assessing, and controlling the hazards of technological processes.

One limitation of the presented methodology is the subjectivity of the experts. To minimize this subjectivity, we assembled a sufficiently large expert panel. Some of the experts worked for regulatory agencies, while others were highly qualified employees of enterprises with CHSs who were responsible for their safe operation. Criterial parameters and their weights were agreed upon until expert consensus was reached. It is also important to note the static nature of the risk assessment. The method used assesses risks at a specific point in time. For reliable monitoring, it is advisable to conduct risk assessments at regular intervals to track the manufacturing process over time. During the methodology development stage, we analyzed the most common methods, which served as its foundation. The lack of external validation makes it relevant to compare the risk assessment results obtained using our methodology with similar results obtained using more common risk assessment methods in the chemical industry.

4. CONCLUSIONS

The methodology presented in the article allows users to comprehensively assess the risks to personnel associated with the operation of chemically hazardous sites: the risk of incidents and accidents, and work-related injuries. The developed methodology for assessing the risk of accidents based on expert assessments, unlike existing ones, also assessesъs the contribution of production equipment and HCs in circulation at chemically hazardous sites to the development of man-made emergency risks at such sites. Analysis of questionnaires completed by experts allows specialists to identify the most vulnerable areas in the enterprise’s production process safety management system, which contributes to the timeliness and effectiveness of corrective measures.

In the future, there are plans to create an automized analytical system based on proven methods for assessing the occupational risks of workers at chemically hazardous sites. This will enable occupational safety services at enterprises and authorized state bodies in the field of industrial safety to quickly obtain objective information about the level of risk both in individual departments and at the enterprise as a whole. In turn, this will become an important basis for the development of preventive and corrective measures that can significantly improve occupational health and safety management system at enterprises with chemically hazardous sites.

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