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Improving the industrial safety management system at enterprises with chemically hazardous sites

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ABSTRACT

This study focuses on developing an industrial and occupational safety management system for enterprises that contain chemically hazardous sites. The methodology, based on an expert approach, enabled the authors to design the structure of the risk management system at such enterprises. It also facilitated the identification of clusters and their descriptors, along with their roles in evaluating the state of the safety management system. The proposed methodology features a flexible and universal structure, making it applicable for assessing industrial and occupational safety across different enterprises, taking into account the specific technological aspects of production processes. In this case study, the authors examined the accident rates, injury hazards, and health risks associated with chemically hazardous sites in enterprises located in the Republic of Kazakhstan. The findings of this study provide a methodological approach that industrial enterprises can use to evaluate the effectiveness of their safety management systems. This allows for the development of measures aimed at preventing chemical accidents and reducing their impacts.

1. Introduction

An analysis of the global frameworks governing emergency management, civil defense, and occupational and industrial safety reveals a strong emphasis on preserving the health and lives of workers [1-3]. The statutory instruments regulating these areas comprise multilevel, intricate mechanisms designed to implement preventive measures aimed at averting failures and accidents. Each nation has a hierarchical system of legal documents that oversee labor relations, state control, and supervision in the field of occupational and industrial safety [4]. These current acts serve as effective tools for monitoring and regulating activities related to worker safety in industrial enterprises [5-9].

The potential threats to chemically hazardous sites (CHSs) are significant. Emergencies at these sites can result in particularly dangerous consequences, primarily affecting the operating personnel. Hazards can also arise during normal operations because the chemicals used in industrial processes can adversely affect workers' health due to their inherent properties.

Work-related diseases account for the highest number of worker deaths. According to the latest data from the World Health Organization (WHO) [10], hazardous substances alone cause over 650,000 deaths annually. Globally, injuries account for 19% of all workplace deaths [11]. Between 1998 and 2015, chemical accidents worldwide resulted in health damage to more than 6000 people, one-third of whom died [12]. The most severe consequences are typically observed in developing countries.

This article is devoted to the development of an industrial and occupational safety management system at enterprises containing chemically hazardous sites (CHS). The methodology was developed on the basis of an expert method, the use of which allowed the authors to create the structure of the risk management system at an enterprise with chemically hazardous sites, identify clusters and a set of descriptors included in them, as well as their contribution to assessing the state of the industrial and occupational safety management system. The presented methodology has a flexible and universal structure, which allows it to be used to assess the state of industrial and occupational safety at an enterprise, taking into account the technological features of production processes. In the case study authors determined the class of accident rate, injury hazard, and insalubrity of some enterprises with CHS located in the Republic of Kazakhstan. The results of the work carried out to develop the methodological approach will allow industrial enterprises to assess the level of functioning of the industrial safety management system at the enterprise and, if necessary, develop a set of measures aimed at preventing chemical accidents and reducing the consequences if they occur.

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Kazakhstan, like other countries, faces numerous technogenic threats [4]. These threats are documented in catalogs and safety data sheets of territories [4]. Information from the official website of the Ministry for Emergency Situations of the Republic of Kazakhstan [13] indicates that from 2020 to 2022, approximately 30,000 technogenic emergencies occurred in the country. These accidents resulted in 2000 injuries and 960 deaths. However, due to preventive measures and timely responses, there is a trend towards a decrease in these figures over time.

Enterprises with chemically hazardous sites are characterized by diverse and specific technological processes, unique working conditions, labor process organization, and sanitary and hygienic environments [10]. The organization of work to ensure the safety of the manufacturing process involves selecting and developing an occupational safety management system at the enterprise that best aligns with its primary goal: creating safe and healthy working conditions for employees [4,7]. This study aims to enhance the industrial safety management system for enterprises with chemically hazardous sites. The objective is to develop a methodology to assess labor safety and mitigate the risks of accidents, occupational injuries, and occupational diseases for employees working at these sites.

2. Overview of existing data sources and processing methods

Currently, the most informative databases worldwide regarding accidents and incidents in the chemical process industry (CPI) include the Major Hazard Incident Data Services of the Health Safety Executive in Great Britain, the database of the Chemical Safety and Hazard Investigation Board in the USA, the Failure Knowledge Database in Japan, and the Major Accident Reporting System administered by the European Union. However, there is no standardized structure across these databases due to varying methods of collecting and recording initial information [14]. As a result, structured data cannot fully inform other companies of the risks and dangers that may lead to accidents and emergencies. Similar conclusions were reached by the Organization for Economic Co-operation and Development (OECD) [15].

Most accidents at chemically hazardous sites could have been avoided if managers had drawn appropriate conclusions and effectively applied the available knowledge from previous incidents to develop preventive measures aimed at improving safety. Drogaris [16], emphasized that 95% of accident causes are generally known but recur due to insufficient awareness of prior accidents and incidents [17,18]. Only one-third of the accidents that occur are analyzed to derive conclusions for improving the enterprise safety management system [19]. This indicates that most accident reports are neither informative nor sufficiently useful for CPI managers to learn from previous incidents.

In Kazakhstan, the informativeness of these databases is even lower. According to official data from 2011 to 2021, no accidents leading to injuries have been reported at enterprises with CHSs. Due to flaws in the legislative system, enterprise administrations often avoid informing supervisory organizations about minor incidents and accidents, rendering the available data on failure rates unreliable.

Currently, several methodologies are commonly used for the safety analysis and reliable operation of CHSs. These include checklists, hazard and operability studies (HAZOP), layer of protection analysis (LOPA), hazard surveys such as the Dow fire and explosion index (F&EI), and safety surveys [20,21]. Each methodology has its strengths and limitations, which depend on the chosen safety assessment criteria and the phase of the enterprise life cycle when applied [22,23]. Most safety methods are complex, requiring significant knowledge, training, and practical experience [24,25]. Additionally, these methods are often costly, time-consuming, and their implementation can be delayed. Each safety assessment method demands varying amounts of process information, limiting its applicability to specific stages of an enterprise's design or lifecycle [26]. Generally, most safety assessment methodologies are not well-suited for early design stages when errors can still be corrected with minimal losses, although some methods, such as HAZOP and Dow F&EI, can be used in a reduced form during these stages.

Typically, these methodologies rely on statistical data regarding chemical accidents, incidents, and their causes from national and international databases. However, while developing our methodological approach, we encountered a significant lack of such databases in Kazakhstan. Consequently, we based our approach on the expert method of assessment, which is most effective in the absence of reliable statistical information. Unlike previously studied methodologies, our developed method takes into account the physical and chemical characteristics of the chemicals involved, such as corrosion activity, fire, and explosion hazards, which can influence the formation of an emergency. This research enabled us to create a methodological approach for analyzing and assessing the risk of accidents, injuries, and occupational diseases among personnel at CHSs of industrial enterprises. This approach is based on the creation of multifactor models, the application of statistical analysis, and expert assessment within the decision-making framework. Similar approaches we successfully utilized for comparable purposes [27–29].

The proposed methodology allows specialists to rapidly gather initial data by completing questionnaires at an enterprise. The results obtained through this methodology enable users to assess the current situation at an industrial enterprise with CHSs, focusing primarily on preventing the occurrence and further development of accidents, rather than merely analyzing the consequences of undesirable events.

3. Methodology for assessing the state of industrial and occupational safety at an industrial enterprise with CHSs

The methodology developed by the authors for the 'analysis and assessment of the risk of accidents, work-related injuries, and occupational diseases at CHSs of enterprises' comprises three main components:

1. Accident risk assessment: This involves determining the accident hazard class of an industrial enterprise with CHSs.
2. Occupational injury risk assessment: This involves determining the injury hazard class of an industrial enterprise with CHSs.
3. Occupational disease risk assessment: This involves determining the insalubrity class of the working conditions at an industrial enterprise with CHSs.

The first component utilizes an expert evaluation method for accident risk assessment, while the second and third components rely on statistical analysis of information regarding occupational diseases and injuries available at the enterprise. The primary advantage of the expert evaluation method is its ability to use the experience of experts during project analysis and account for various qualitative factors. This method does not require precise initial data or expensive software and can provide assessments during the design stage of an industrial plant with CHSs. It also allows for straightforward calculations. By using the expert evaluation method, users can visually assess the strengths and weaknesses of the criteria parameters within the clusters that describe accident hazard and severity indicators.

Statistical methods are used to assess risk in individual subdivisions (workshops) and the enterprise as a whole, analyzing work-related injuries and occupational morbidity over a certain period. The simplicity of mathematical calculations is a significant advantage of this method, although it requires a large number of observations to be effective.

3.1. Accident risk assessment and determination of accident hazard class of an industrial enterprise with chemically hazardous sites

The risk of technogenic accidents at CHSs was assessed in three phases:

1. Preliminary study.

2. Gathering and formation of the input database.
3. Evaluation of accident risk levels in CHSs.

The flowchart in Fig. 1 illustrates the sequence of evaluating the risk of accidents from technogenic emergencies at chemically hazardous sites.

The purpose of the preliminary study was to determine sets of criterion parameters for two risk components: the hazard index of CHSs and the vulnerability index of personnel working at these sites. The established criteria set is used to quantify the hazard index, which assesses the probability of an accident, while the vulnerability index characterizes the degree of personnel vulnerability to the destructive factors of a technogenic emergency.

The methodology for forming the expert group and the stages of expert research have been detailed in earlier articles by the authors [29, 30].

As a result of the expert research, the following were established:

1. The main directions (clusters) influencing the hazard indices of CHSs and the vulnerability of enterprise personnel (Tables A.1 and A.6).
2. Weight coefficients for each cluster when determining the corresponding index (hazard, vulnerability) (Tables A.1 and A.6).
3. A set of descriptors necessary for the complete description of clusters (Tables A.2–A.6).
4. Weight coefficients and value ranges for each descriptor to assess the outcome of technogenic emergencies (Tables A.2–A.6).
5. Final survey questionnaires for industrial enterprises concerning the hazard and vulnerability of CHSs.

The accident hazard index at a CHS was determined by the total

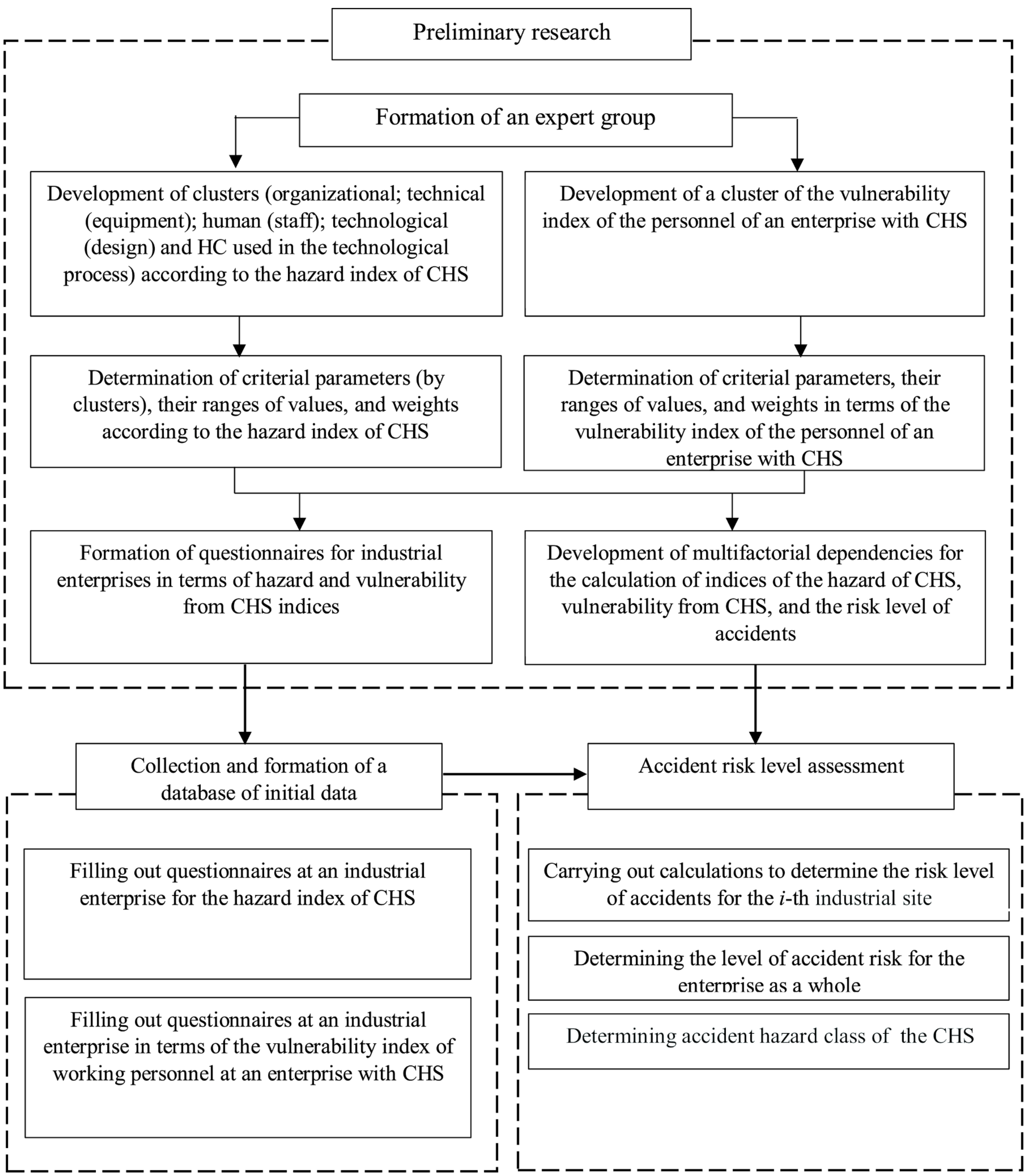

Fig. 1. Flowchart of the risk assessment process for man-made accidents at chemically hazardous sites.

influence of factors grouped by their direction and organized into four clusters:

1. Organizational desciptors for assessing the industrial safety management system at the enterprise.
2. Technical descriptors for assessing the industrial safety management system concerning the equipment used at the enterprise.
3. Human (personnel working at the industrial enterprise) descriptors for assessing the industrial safety management system at an enterprise.
4. Technological descriptors for assessing the industrial safety management system, considering the hazardous chemicals used in the technological process.

The set of indices that constitute the cluster of ‘organizational descriptors for assessing the industrial safety management system at the enterprise’ determines the management’s policy for monitoring, organizing, and managing industrial safety. This includes checking the state of systems and the enterprise’s territory to prevent contributions to emergencies according to specific scenarios.

When forming the cluster for ‘technical descriptors for assessing the industrial safety management system at the enterprise’ (pertaining to the equipment used at the enterprise), the expert group focused on the critical technological equipment involved in the industrial process and its conditions. Additionally, special attention was given to safety management controls and auxiliary systems, such as localization means and systems for release and ventilation. The features and specifics of the processing line were also considered when assessing the efficiency of these control measures.

The selection of descriptors included in the cluster of ‘human (personnel working at an industrial enterprise) descriptors for assessing the industrial safety management system at an enterprise’ is determined by the need for constant monitoring of the fulfillment of all functional requirements by personnel working at the industrial enterprise, including contractors.

The ‘technological descriptors for assessing the industrial safety management system at the enterprise, taking into account the HC used in the technological process’, were developed based on an assessment of the compliance of industrial sites and systems with initial design solutions and subsequent modernization. This includes the quantity and characteristics of the HC used in the technological process. When evaluating these descriptors, the basic management strategy established at the enterprise and all stages of the enterprise’s lifecycle—such as startup, normal operation, and emergency shutdowns—were considered.

When creating the cluster describing the vulnerability index of personnel at a chemically hazardous site, the expert group considered measures and actions aimed at assessing the state of personnel protection at workplaces and throughout the enterprise. The data were grouped into three main categories:

1. Availability of time for evacuation and other measures in case of failure.
2. Availability of protective structures and other means of collective protection.
3. Availability of personal protective equipment.

This categorization enabled the authors to develop matrices for assessing clusters and descriptors that describe the state of the enterprise’s industrial safety system in terms of hazard and vulnerability, as detailed in Appendix A.

For more convenient and objective analysis, our methodology assigns five possible numeric values to the descriptors, allowing for a more detailed assessment of the hazard posed by the CHS.

During the preliminary research stage (Fig. 1), it is crucial to accurately determine the weights of the descriptors and clusters. Due to the lack of reliable statistical data on the causes of accidents and incidents in enterprises with CHSs in Kazakhstan, we based our analysis on the statistical outputs from international databases [31]. This approach enabled us to determine weight coefficients for each cause of accidents.

The results of these studies allowed us to evaluate the overall effectiveness of the safety management system at an enterprise with a CHS. For specific enterprises, and considering the characteristics of production processes involving hazardous chemicals, adjustments can be made to the weight values of descriptors to reflect their influence more accurately.

The second stage of assessing the risk of accidents at a CHS involved gathering and forming an input database through a questionnaire survey of enterprise personnel (Fig. 1). These questionnaires comprise tables that collect information in relevant areas (clusters), enabling researchers to precisely assess each descriptor and assign a value according to a scoring system. This stage completes the preliminary studies for assessing the risk of technogenic emergencies at CHSs, allowing us to proceed directly to the practical calculations in the ‘evaluation of accident risk level at CHSs’ block.

The survey data from experts, along with the equations developed based on these data, facilitated the calculation of both the hazard index of a CHS and the personnel vulnerability index. Based on these results, we can evaluate the overall accident risk level at an enterprise with CHSs.

3.1.1. Calculation and assessment of the hazard index of a chemically hazardous site

The first stage of ‘carrying out calculations to determine the risk level of accidents for the *i*-th industrial site’ is to determine the hazard index of the chemically hazardous sites.

The accident hazard index for the *i*-th industrial site of the enterprise is determined based on the degree of influence of a set of criterion parameters $\{n\}$ and the significance of their values (1).

$$HI_i = \sum_{k=1}^{4} \sum_{j=1}^{n} w_{kj} \cdot f_{kj}, \tag{1}$$

where k denotes a cluster of descriptors describing the state of the industrial safety management system of the enterprise; w_{kj} denotes the weight of the j-th descriptor in the k-th cluster. f_{kj} denotes the score value of the descriptor from the k-th cluster; n is the number of descriptors for the k-th cluster of the CHS hazard index.

Using the data presented in Appendix A, the hazard index of a CHS for the i-th workshop with HC and/or the entire enterprise is determined as

$$\begin{aligned} HI_i = {} & \big(0.047(f_{11}+f_{18})+0.034f_{12}+0.015(f_{13}+f_{14})+0.065f_{15}+0.068f_{16} \\ & +0.021f_{17}+0.02f_{19}++0.056f_{110}+0.01f_{111}+0.007f_{112}+0.025f_{113}\big) \\ & +\big(0.023f_{21}+0.014f_{22}+0.011(f_{23}+f_{24})+0.046f_{25}+0.035f_{26}+0.025f_{27} \\ & +0.02f_{18}+0.029f_{29}+0.026f_{210}+0.01f_{211}\big)+\big(0.034f_{31}+0.01f_{32}+0.031f_{33} \\ & +0.015f_{34}\big)+\big(0.038f_{41}+0.023f_{42}+0.016f_{43}+0.017f_{44}+0.021f_{45} \\ & +0.013(f_{46}+f_{411})+0.024f_{47}++0.015f_{48}+0.02f_{49}+0.01f_{410}\big). \end{aligned} \tag{2}$$

According to the cluster of ‘organizational descriptors for assessing the industrial safety management system at the enterprise’:

f_{11} is the score for organization of training in industrial safety management;
f_{12} is the score for the functioning of the department (person responsible) for industrial and occupational safety in an enterprise.
f_{13} is the score for the availability of a full set of technical documentation, accounting logs and certificates.
f_{14} is the score for periodic revision of instructions and schemes;
f_{15} is the score for completing written work procedures and tasks with clear instructions;

f_{16} is the score for process hazard (risk) analysis (PHA) for process hazards identification, assessment, and control;
f_{17} is the score for the application and verification of the state of systems of control equipment (CE) and automation equipment systems.
f_{18} is the score for the periodic inspections of workplaces, compliance of equipment and construction with design specifications, and industrial safety requirements.
f_{19} is the score for monitoring the maintenance of the territory of the enterprise (site) in an appropriate order (accident-free conditions).
f_{110} is the score for the availability of staff feedback with management regarding process risk analysis and other process control elements. Availability of safety incentive programs
f_{111} is the score for the availability of a detailed contingency plan and training sessions.
f_{112} is the score for periodic audit of industrial safety management;
f_{113} is the score for the maintenance of auxiliary systems (ventilation, heating, and sewage) at workplaces, sites, and the enterprise as a whole, in proper order.
According to the following cluster of 'technical descriptors for assessing the industrial safety management system at the enterprise' *(*for the equipment used at the enterprise*)*:
f_{21} is the score for pressurized vessels;
f_{22} is the score for separation equipment;
f_{23} is the score for chemical reactors;
f_{24} is the score for heat exchange equipment;
f_{25} is the score for length of pipeline systems transporting CH;
f_{26} is the score for wear coefficient of fixed assets;
f_{27} is the score for the replacement coefficient of fixed assets;
f_{28} is the score for the capacity of pumps (compressors);
f_{29} is the score for the number of storage tanks of the CH at the site.
f_{210} is the score for controls (control devices, alarms, sensors, interlocks, and availability of safety systems, including automatic shut-off valves).
f_{211} is the score for the availability of means of localization, systems, and devices for release and ventilation.
According to the cluster, 'human (personnel working in an industrial enterprise) descriptors for assessing the industrial safety management system at an enterprise':
f_{31} is the score used to evaluate the level of knowledge regarding personnel safety rules and industrial instructions.
f_{32} is the score for the conformity of contractors' knowledge with safety rules and production processes (similar to item f_{31}).
f_{33} is the score for staffing of brigades;
f_{34} is the score for the schedule of the labor process;

According to the cluster of 'technological (project) descriptors for assessing the industrial safety management system at the enterprise, taking into account the HC used in the technological process.'

f_{41} is the score for the functioning of the change process management system;
f_{42} is the score for compliance with the design solutions of buildings and construction, warehouses, and places of safekeeping for the HCs.
f_{43} is the score for compliance with the design solutions for protective and safety devices and control equipment.
f_{44} is the score for compliance with the design of ventilation, heating, sewerage, plumbing, and lighting systems at workplaces, sites, and enterprises.
f_{45} is the score for compliance with the design of the operation of the processing lines and new equipment.
f_{46} is the score for data on corrosivity;
f_{47} is the score for storage volume;
f_{48} is the score for hazard classes of chemical products;
f_{49} is the score for hazard classes of explosive chemical products;
f_{410} is the score for temperature class;
f_{411} is the score for combustibility group.

3.1.2. Calculation and assessment of the vulnerability index of working personnel when exposed to a destructive factor as a result of technogenic emergencies at a CHS

The second step of 'carrying out calculations to determine the risk level of accidents for the *i*-th industrial site' is to determine the vulnerability index of the working personnel under the impact of a destructive factor as a result of man-made emergencies at a chemically hazardous site.

The vulnerability index for working personnel located in the zone of action of the destructive factor is determined based on the degree of influence of a set of criterion parameters $\{m\}$ and the significance of their values:

$$VI_i = \sum_{j=1}^{m} a_j \cdot y_j, \tag{3}$$

where a_j denotes the weight of the *j*-th descriptor of vulnerability; y_j denotes the score for the vulnerability descriptor; m is the number of descriptors that form a cluster to assess the vulnerability index of the working personnel.

Using the data presented in Appendix A, the vulnerability index of working personnel exposed to a destructive factor affected by technogenic emergencies at a CHS was determined as follows:

$$\begin{aligned} VI_i &= 0.4y_1 + 0.1(y_2 + y_3) + 0.03y_4 + 0.07y_5 \\ &+ 0.05(y_6 + y_7 + y_9) + 0.09y_8 + 0.06y_{10}, \end{aligned} \tag{4}$$

where according to the cluster of descriptors for the vulnerability index of the working personnel of an industrial enterprise from a CHS:

y_1 is the score for availability of time for evacuation and other urgent measures in the case of an accident;
y_2 is the score for 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 hardware room;
y_3 is the score for the presence of protective structures;
y_4 is the score for the presence of identification marks, fences, light signaling, removable lockable shields, warning alarms, warning posters;
y_5 is the score for the presence of systems of aspiration, ventilation, dust suppression, disposal and localization of harmful substances;
y_6 is the score for the presence of remote devices and controls, control systems, provision of protection against self-starting, round-the-clock surveillance;
y_7 is the score for the presence of safety devices;
y_8 is the score for the presence of local ventilation systems, local suction systems, individual sewage, water supply and protective devices;
y_9 is the score for the presence of personal protective equipment in the workplace;
y_{10} is the score for the supply of enterprise personnel with personal protective equipment.

3.1.3. Assessment of the accident risk level as a result of emergencies

The risk level of accidents resulting from emergencies at CHSs is defined by a combination of several risk components: the hazard index for all clusters describing the state of the industrial safety management system at an enterprise, and the vulnerability index of the working personnel at the industrial enterprise.

Table 1 provides the matrix to facilitate the risk assessment procedure, coding six risk levels: none, insignificant, low, moderate, high, and critical.

Based on the calculated hazard and vulnerability indices and the data

Table 1
Matrix for assessing the risk level man-made accidents at chemically hazardous sites for the *i*th workshop and/or the entire industrial enterprise.

Hazard index	Vulnerability index				
	0	up to 2	2 - 3	3 - 4	4 - 5
0	none	none	none	none	none
up to 2	none	insignificant	low	moderate	high
2 - 3	none	low	moderate	high	high
3 - 4	none	moderate	high	high	critical
4 - 5	none	high	high	critical	cririical

in Table 1, the risk level of accidents caused by emergencies at a CHS for the *i*-th workshop and/or the entire enterprise was determined. For the general level of accident risk, the highest level obtained among all *i*-th workshop with HC was selected (determining the level of accident risk for the enterprise as a whole).

The accident hazard class of the CHS was determined based on the results of the accident risk level assessment (Table 2). Each accident risk level corresponds to its own accident hazard class. An insignificant risk of an accident (or its absence) corresponds to Class V accident hazards; in this case, the industrial site is relatively safe, Class IV accident hazard is a low level of risk, Class III is a moderate level, and so on (determining accident hazard class of the CHS block).

The calculation of risks for the *i*-th workshop with HC allowed to create an overall picture from the standpoint of the safety of the operation of the enterprise as a whole. This information enables the development of arrangements and instructions focused on decreasing the risk level of an accident in an enterprise with a CHS.

3.2. Assessment of the risk of work-related injuries and determination of the injury hazard class of an industrial enterprise with CHS

The initial data for assessing the risk of work-related injuries are:

1. Number of accidents at enterprise (in its subdivisions) over the study period.
2. Average quantity of workers in the industrial enterprise (in its subdivisions) over the study period.
3. Grade of permanent disability of employees as a result of injuries received during the study period (in accordance with the conclusion of medical and social expertise (MSE)).

Considering the results of the risk assessment of occupational trauma, industrial enterprises with CHS were classified according to their grade of trauma risk. Simultaneously, a risk assessment can be carried out for both a separate unit and the entire site.

The classification of industrial enterprises with CHS, depending on the degree of injury hazard, was realized by considering the outcomes of the risk assessment of occupational trauma, both for a separate unit and for the entire site.

Table 2
Determination of the accident hazard class for a chemically hazardous site.

Accident risk level	Accident hazard class	Accident hazard class characteristic
Critical	Class I	Chemically hazardous site of extremely high hazard
High	Class II	Chemically hazardous site of high hazard
Moderate	Class III	Chemically hazardous site of moderate hazard
Low	Class IV	Chemically hazardous site of low hazard
None or insignificant	Class V	Chemically hazardous site of insignificant hazard

Two indices were used to evaluate the risk of occupational trauma: frequency of work-related injuries and their severity (disability). The work-related injury frequency coefficient is calculated using Eq. (5).

$$C_F = \frac{n}{N}, \tag{5}$$

where n is the number of injured employees in a manufacturing enterprise in the previous year.

N is the average number of workers at a manufacturing enterprise in the previous year.

As an acceptable risk of occupational injury, a value of 1×10^{-6} [27] is accepted as the maximum allowable value for any risk, including the industry.

The severity of work-related injuries in workers is evaluated by the value of their long-term loss of general ability to work. According to the current rules [32], the territorial departments for labor and social protection of the population conduct a medical and social examination of employees, which determines the degree of disability. Upon completing the MSE, an injured worker receives a certificate indicating the degree of permanent disability. This document enables researchers to evaluate the severity of work-related injuries.

For the entire enterprise, the coefficient of the severity of harm to the health of workers as a result of a work-related injury (according to the degree of permanent disability) is determined by Eq. (6):

$$C_{S_j} = \frac{\sum_{i=1}^{n} W_i}{n}, \tag{6}$$

where n is the quantity of traumatized workers at the enterprise;

W is the value of the long-term disability of the i-th injured worker, as determined by the MSE.

The coefficient of the severity of harm to the health of workers as a result of work-related injuries, calculated by Eq. (6), is estimated in accordance with the gradation [27].

If one or more fatal accidents occurred at an industrial site during the study period, the severity of the work-related injuries at the entire industrial site was assessed as extremely severe.

To conduct a comprehensive analysis of work-related injuries, this methodological approach allowed us to conduct a detailed assessment of the risk level of occupational injuries to the level of a definite industrial site of an enterprise with a CHS.

The risk level of occupational injuries in an enterprise with CHS is determined based on calculations of the coefficients of the frequency and severity of the employee's work-related injury. Thus, the matrix listed in Table 3 was created. This allowed us to assess the risk of occupational injury at industrial sites. It demonstrates several combinations of the injury frequency coefficient with the severity of harm to health, and six levels of risk were established: none, insignificant, low,

Table 3
Matrix for assessing the risk level of work-related injuries at industrial sites.

Coefficient of work-related injury frequency C_F	Coefficient of the severity of harm to the health of workers C_S				
	0	up to 10	10 - 33	33 - 100	fatal accident
0	none	none	none	none	none
up to 10^{-6}	none	insignificant	insignificant	low	critical
10^{-6} - 10^{-4}	none	insignificant	low	moderate	critical
10^{-4} - 10^{-3}	none	low	moderate	moderate	critical
10^{-3} - 10^{-2}	none	moderate	moderate	high	critical
more than 10^{-2}	none	high	high	critical	critical

moderate, high, and critical.

Furthermore, the results of the occupational trauma risk evaluation allowed us to determine the injury hazard class for the entire enterprise. As shown in Table 4, each occupational trauma risk level corresponds to a certain injury hazard class.

3.3. Assessment of the risk of developing occupational diseases and determination of the insalubrity class of labor conditions of an industrial enterprise with CHS

The input data used for calculating the risk of developing occupational diseases include:

- number of workplaces at the industrial site in the *i*-th class of labor conditions;
- total number of workplaces at the industrial site
- average number of employees at industrial site
- number of employees at an industrial site with newly diagnosed occupational disease.

The current standards [33,34] recommend "besides the results of a hygienic assessment of labor conditions, to use materials from periodic medical examinations, physiological, laboratory and experimental studies, as well as epidemiological data" to prove occupational risks [34].

Thus, it is possible to determine the risk of developing occupational diseases among workers at an industrial site using the ratio of the average index of the hazard class of labor conditions at workplaces at an industrial site to the number of workers at an industrial site with newly diagnosed occupational diseases. Based on the classical definition of risk, the number of workers at an industrial site with newly diagnosed occupational diseases determines the frequency of an unfavorable event, and the class of insalubrious labor conditions at the workplace determines its severity.

Table 4
Determination of the injury hazard class at a chemically hazardous site.

Risk level of work-related injuries	Injury hazard class	Characteristic of injury hazard class
Critical	Class I	Chemically hazardous site of extremely high hazard
High	Class II	Chemically hazardous site of high hazard
Moderate	Class III	Chemically hazardous site of moderate hazard
Low	Class IV	Chemically hazardous site of low hazard
None or insignificant	Class V	Chemically hazardous site of insignificant hazard

The insalubrity index of the labor conditions of an industrial site is determined in the following stages:

Stage 1. In the first stage, the structure of the CHS was studied, and the total number of workplaces was determined for all sections of the main production process. The number of workplaces was determined by considering the specifications of the industrial site, brand of equipment, period of operation, and impact of harmful factors on the industrial environment.

It is necessary to consider the workplaces involved in the main production processes of hazardous chemicals to define the insalubrity class of the labor conditions of the entire industrial enterprise.

Stage 2. The class of labor conditions, depending on the degree of insalubrity and danger, was determined for each workplace of the industrial site in accordance with the degree of deviation of the actual values of the effects of the labor environment from hygienic standards. It can also be established by the attestation of workplaces according to labor conditions [33,34]. Based on the hygiene criteria, four classes of labor conditions were distinguished depending on the grade of insalubrity: optimal, permissible, insalubrious (4 subclasses), and dangerous.

Stage 3. Workplace working conditions were determined. The class of working conditions as a whole for the workplace is taken according to the maximum index from the obtained values of the class of working conditions for all sanitary and hygienic factors [35]. If there are three or more identical maximum indices of a class of labor conditions, the class following them is considered.

Stage 4. In accordance with the class of working conditions at the workplace, the insalubrity index of labor conditions I_{ins} at the CHS for the entire enterprise is calculated using Eq. (7):

$$I_{ins} = \frac{\sum_i^7 n_i \times R_i}{N_w}, \tag{7}$$

where n_i is the number of workplaces at the industrial site in the *i*-th class of working conditions.

R_i is the numerical value of the *i*-th class of working conditions (for class 1, the value is 1; for class 2, the value is 2; for class 3.1, the value is 4; for class 3.2, the value is 8; for class 3.3, the value is 16; for class 3.4, the value is 32; and for class 4, the value is 64).

N_w is the total number of workplaces at the industrial site.

The frequency coefficients of newly diagnosed occupational diseases were determined using the following steps.

Stage 1. The number of newly diagnosed occupational diseases confirmed by specialized medical institutions was determined based on the CHS discovered during the study period.
Stage 2. The total number of workers at the CHS is determined.
Stage 3. The frequency coefficient C_{FOD} for newly diagnosed occupational diseases per 10,000 employees was calculated using Eq. (8).

$$C_{F_{OD}} = \frac{n_{OD}}{N} \times 10000, \tag{8}$$

where n_{OD} is the number of newly diagnosed cases of occupational diseases among employees at an industrial site over the previous year.

N is the total quantity of employees at the industrial site.

The risk of developing occupational diseases in employees of an enterprise with CHS was assessed using a previously determined index of the insalubrity of the working conditions of an industrial facility and the index of the frequency of newly diagnosed occupational diseases. In this regard, a matrix was developed for risk assessment of the occupational sickness rate at an industrial site (Table 5). It has several combinations of the aforementioned indices and establishes five levels of risk: none, low, medium, high, and extremely high.

The assessment results of the risk level of occupational diseases among workers at industrial sites determined the hazard class of an enterprise (workshops with HC), as shown in Table 6. According to them, each risk level of occupational sickness among workers at industrial sites corresponds to an insalubrity class in a CHS.

Thus, the insalubrity indicator of labor conditions in industrial enterprises with CHS is determined as follows:

1. Objectively analyze the degree of insalubrity of labor conditions at CHSs.
2. Assess the risk of developing occupational diseases among employees of enterprises where CHS are located.
3. Define the insalubrity class of the enterprise as a whole.
4. Making administrative decisions based on objective information, focusing on the prevention of occupational diseases, and controlling the performance of preventive measures in industrial enterprises with CHS.

4. Results and discussion

The presented methodology follows a uniform pattern to define and evaluate the risk levels of accidents, work-related injuries, and occupational diseases among working personnel, and to analyze the condition of the safety management system in enterprises with CHSs. Creating a unified information-analytical database with a list of criteria, their value ranges, and weights, with the participation of experts, is the most challenging task. This complexity arises from the need to form representative data arrays, which are clusters of descriptors used to determine the required indicators. These arrays should comprehensively describe the functional state of the industrial and occupational safety systems operating in an enterprise.

The methodology has been tested at several enterprises in various economic sectors in Kazakhstan, including *Kazakhmys Smelting* LLP in Balkhash and Zhezkazgan, the *Mineral Fertilizers* factory of *Kazphosphate* LLP in Taraz, *Kainar* LLP in Taldykorgan, *KazAzot* JSC in Aktau, and *Kaustik* LLP in Pavlodar.

The conducted research enabled the following:

1. Collect primary information using the developed survey questionnaires in collaboration with representatives of specialized industrial and occupational safety services at the enterprises. The initial data array included numerical values for each criterion parameter of the clusters in the assessment matrices (Appendix A). These clusters describe the state of industrial safety of the enterprise based on hazard and vulnerability characteristics (to assess the risk of accidents at enterprises with CHSs) and the parameters for calculating the risk of work-related injuries and occupational diseases.
2. Conduct a point evaluation of each numerical value for the criterion parameters across all clusters characterizing the hazard and vulnerability of the enterprise, based on the gathered information. The point values, along with the numerical values of the parameters for calculating the risk of work-related injuries and the risk of developing occupational diseases, form an array of initial data for further calculations for each research object. Appendix B presents the final array of initial data for all enterprises and their subdivisions (workshops) where the methodology was tested.
3. Calculate the levels of accident risk, work-related injuries, and occupational diseases among personnel due to possible emergencies for each enterprise, as well as their subdivisions (workshops) with HCs where approval was carried out. Determine the accident rate, injury hazard, and insalubrity of enterprises with CHSs. The results of these calculations are summarized in Table 7.

Table 6
Determination of the hazard class for an industrial enterprise (workshop).

Risk level of developing occupational diseases	Insalubrity class	Characteristics of the insalubrity class of labor conditions
Extremely high risk	Class I	Industrial site of extremely high danger
High (unendurable) risk	Class II	Industrial site of high danger
Moderate (essential) risk	Class III	Industrial site of medium danger
Low (minor) risk	Class IV	Industrial site of low danger
Absence of risk/ negligible (endurable) risk	Class V	Industrial site of negligible danger

Table 5
Matrix for calculating the risk level of developing occupational diseases among employees at industrial sites.

Insalubrity index of labor conditions at the CHS, I_{ins}	Frequency coefficient for newly diagnosed occupational diseases, $C_{F_{OD}}$					
	0	0 - 1,5	1,5 - 5	5 - 15	15 - 50	more than 50
1	none	none	none	none	low	low
1 - 2	none	low	low	low	low	medium
2 - 4	low	low	low	low	medium	medium
4 - 8	low	low	medium	medium	medium	medium
8 - 16	low	medium	medium	medium	medium	high
16 - 32	medium	medium	medium	medium	high	Extremely high
32 - 64	medium	medium	medium	high	Extremely high	Extremely high

Table 7
Summarized results for calculating indices to assess the risk of accidents, work-related injuries, and occupational diseases.

No.	Name of the enterprise (workshop)	Hazard index, HI	Vulnerability index, VI	Accident risk level	Accident hazard class	Coefficient of the severity of harm to the health, C_{S_j}	Work-related injury frequency coefficient, C_F	Risk level of work-related injuries	Injury hazard class	Insalubrity index of labor conditions at the industrial site I_{ins}	Frequency coefficient for newly diagnosed occupational diseases C_{FOD}	Risk level of developing occupational diseases	Insalubrity class
1	*Kainar* LLP, Taldykorgan	2.061	1.26	small	IV	0	0	none	V	2.1	0	low	IV
2	Workhop of precious metals, *Kazakhmys Smelting* LLP, Balkhash	1.661	1.09	insignificant	V	0	0	none	V	2.7	0	low	IV
3	Workhop of sulphuric acid, *Kazakhmys Smelting* LLP, Balkhash	1.969	1.09	insignificant	V	0	0	none	V	2.7	0	low	IV
4	Workhop of copper electrolysis, *Kazakhmys Smelting* LLP, Balkhash	2.162	1.18	small	IV	15%	0.0015	moderate	III	2.37	0	low	IV
	On the whole for the enterprise *Kazakhmys Smelting* LLP, Balkhash			small	IV			moderate	III			low	IV
5	Workhop of sulphuric acid, *Kazakhmys Smelting* LLP, Zhezkazgan	2.41	1.2	small	IV	fatal	0.005	critical	I	2.57	0	low	IV
6	Workhop of copper electrolysis, *Kazakhmys Smelting* LLP, Zhezkazgan	1.758	1.48	insignificant	V	20%	0.0099	moderate	I	2.76	19.8	medium	III
	On the whole for the enterprise *Kazakhmys Smelting* LLP, Zhezkazgan			small	IV			critical	I			medium	III
7	Ammonia production workshop, *KazAzot* JSC, Aktau	2.212	1.56	small	IV	0	0	none	V	2	0	none	V
8	Workshop of weak nitric acid, *KazAzot* JSC, Aktau	2.424	1.16	small	IV	20%	0.0133	high	II	2	0	none	V
9	Workshop for the production of complex mineral fertilizers, *KazAzot* JSC, Aktau	2.159	1.16	small	IV	60%	0.0039	high	II	2	0	none	V
	On the whole for the enterprise *KazAzot* JSC, Aktau			small	IV			high	II			none	V
10	Workhop of sulphuric acid, *Mineral Fertilizers* factory of *Kazphosphate* LLP, Taraz	2.412	1.0	small	IV	fatal	0.0091	critical	I	3	0	low	IV
11	Workshop of ammophos, *Mineral Fertilizers* factory of *Kazphosphate* LLP, Taraz	2.408	1.4	small	IV	fatal	0.009	critical	I	2.27	22.2	medium	III
12	Workshop for the production of fodder defluorinated phosphates, *Mineral Fertilizers* factory of *Kazphosphate* LLP, Taraz	1.678	1.0	insignificant	V	0	0	none	V	3	0	low	IV
	On the whole for the enterprise, *Mineral Fertilizers* factory of *Kazphosphate* LLP, Taraz			small	IV			critical	I			medium	III
13	*Kaustik* LLP, Pavlodar	2.157	1.12	small	IV	32.5%	0.004	moderate	III	2	0	none	V

Table 7 provides a line-by-line summary of the final results of the main indicators for each enterprise and their subdivisions (workshops). These indicators were used to assess the levels of accident risk, work-related injuries, and occupational diseases, as well as the classes of accident risk, injury hazard, and insalubrity. The scoring results (Appendix B) allowed for the assessment of the influence of each criterion parameter on the accident risk level of the enterprise. During a critical analysis, particular attention should be paid to the criterion parameters whose point values range from three to five and to the dominant values of the weight coefficients. These are according to the matrix of evaluation of clusters describing the state of the industrial safety system of the enterprise by indices of hazard and vulnerability (Appendix A).

Following this analysis, it appears that enterprises pay insufficient attention to analyzing existing hazards and applying methods for identifying and assessing risks associated with industrial processes. A significant contribution to the total value of the hazard index (HI_i) is made by descriptors related to the equipment used by enterprises with CHSs. This is primarily due to the complexity of technological processes and the labor-intensive nature of production, which necessitate the use of modern specialized equipment. Additionally, many of the studied sites operate on a round-the-clock schedule because technological processes at CHSs require uninterrupted work in three shifts, further contributing to the hazard index.

Moreover, the significant volumes of hazardous chemicals used in production processes create an aggressive environment that leads to the corrosion of equipment blocks. When multiple hazardous chemicals are used in a CHS, the highest scoring chemical is used to calculate the risk of an emergency. In general, the accident risk level is "small" or "insignificant" at all study sites, corresponding to classes IV and V of accident hazard for a CHS. These indices indicate that enterprises are consistently implementing a range of technical and organizational measures aimed at maintaining a high level of efficiency in their industrial safety management systems. An analysis of each cluster and its descriptors allowed for an assessment of their impact on the overall risk level of accidents. This facilitated the development of measures aimed at reducing this risk and improving the functioning of the enterprise's industrial safety management system.

There was no consistent trend in the level of injury across the study participants. During the study period, half of the subjects experienced isolated accidents leading to injuries of varying degrees of long-term disability. Fatal accidents have also been reported in the literature. In the studied group of sites, the injury rate ranged from *none* to *critical*, corresponding to classes I and V of trauma risk at a CHS. Based on the findings from accident investigations at enterprises, we developed a comprehensive set of measures aimed at preventing the recurrence of such accidents. Investigations have shown that these accidents were often the result of unsafe actions by working personnel.

Based on the hygienic assessment of labor conditions, materials from periodic medical examinations, physiological, laboratory, and experimental studies, and epidemiological data, isolated cases of newly diagnosed occupational diseases were identified among employees at industrial sites. The risk of occupational diseases among workers in the studied enterprises ranges from *none* to *medium*, corresponding to insalubrity classes V and III at a CHS. This analysis allowed us to assess the situation regarding occupational diseases, make evidence-based administrative decisions for their prevention, and monitor the effectiveness of preventive measures implemented at industrial enterprises with CHSs.

5. Conclusions

Several studies have focused on the development of industrial and occupational safety management systems in enterprises, highlighting their continued relevance. The authors conducted a series of studies, resulting in the development of the 'methodology for the analysis and assessment of the risk of accidents, work-related injuries, and occupational diseases of personnel at chemically hazardous sites of enterprises'. This methodology, developed using the expert method, allowed for the definition of clusters and a set of criteria parameters, as well as their contributions to assessing the state of the industrial and occupational safety management system.

This methodological approach enables a comprehensive addressing of industrial and occupational safety issues in enterprises with CHSs by synthesizing three main areas:

1. Risk evaluation of accidents and determination of accident hazard classes for enterprises with CHSs.
2. Risk evaluation of developing occupational diseases and determination of the insalubrity class of an enterprise with CHSs.
3. Risk evaluation of work-related injuries and determination of the injury hazard class of enterprises.

The experimental studies carried out by the authors enabled the development of questionnaires and the calculation and assessment of the risk levels for accidents, work-related injuries, and occupational diseases among personnel at enterprises with CHSs, including their subdivisions (workshops) with HCs. The accident rate, injury hazard, and insalubrity of an enterprise with CHS were determined based on this comprehensive approach.

This article presents calculations to evaluate the risk levels of accidents, work-related injuries, and the development of occupational diseases among employees at CHSs in selected enterprises. The classes of accident hazards, injury hazards, and insalubrity for these enterprises were determined. An analysis of the score evaluation of the criteria parameters allows specialists to develop organizational and technical measures aimed at reducing the hazard and vulnerability indicators of CHSs, thereby decreasing the level of accident risk resulting from emergencies.

The practical significance of this research lies in its ability to:

1. Form conclusions and evaluate the effectiveness of the industrial safety management system for enterprises with CHSs.
2. Assess and consider the specific features of technological processes at CHSs.
3. Develop recommendations and effective preventive measures aimed at reducing the risks of accidents, injuries, and occupational diseases among workers at CHSs.
4. Provide supervisory organizations with up-to-date information and forecasts on labor safety in enterprises with CHSs, thereby increasing the effectiveness of ongoing preventive and operational measures.
5. Improve occupational risk management by conducting comprehensive assessments and evaluations of the risks of accidents, occupational injuries, and diseases, and by calculating and predicting the quantitative safety characteristics that can be controlled at specific technological sites or processes. This, in turn, will reduce the financial expenses associated with mitigating damage to the industrial environment and labor processes.
6. Enhance industrial safety management systems in the CHSs of industrial enterprises.

The presented methodology forms the basis for a developed information-analytical system for monitoring and assessing the risks of accidents, work-related injuries, and occupational diseases in enterprises with CHSs in the Republic of Kazakhstan. This system allows users to automatically calculate risk levels.

The main limitation of this methodology is the accuracy of the initial baseline information gathering, which is influenced by the "human factor." This can result from insufficient qualifications of the working staff or deliberate underestimation of indicators when completing survey questionnaires. Such issues often arise due to the imperfections in the legal system, where enterprise administrations may avoid informing supervisory organizations about existing shortcomings in the operation of the occupational safety system.

Ethics statement

The research described in this article was conducted in accordance with the ethical standards established by the Law of the Republic of Kazakhstan *On Science* dated February 18, 2011 № 407-IV and *Regulations on Research Ethics* of Abylkas Saginov Karaganda Technical University. The authors' activities do not violate the principles coming from the fundamental human rights to freedom of research and respect for the rights and legitimate interests of research participants.

CRediT authorship contribution statement

Pavel V. Yemelin: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sergey S. Kudryavtsev:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Natalya K. Yemelina:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Evaluation matrices for clusters and criteria parameters describing an enterprise's industrial safety system in terms of hazard and vulnerability indices (by scores and weights).

Table A.1
Evaluation of the weight of clusters describing the hazard index of a chemically hazardous site.

Cluster name	The total value of the weight coefficient for the cluster
Cluster of organizational criterial parameters for assessing the industrial safety management system at the enterprise	0.43
Cluster of technical criterial parameters for assessing the industrial safety management system at the enterprise (for the equipment used at the industrial enterprise)	0.25
Cluster of human (personnel working at an industrial enterprise) criterial parameters for assessing the industrial safety management system at an enterprise	0.09
Cluster of technological (design) criterial parameters for assessing the industrial safety management system at the enterprise, taking into account the HC used in the technological process (physicochemical, toxicological and other properties of a hazardous chemical)	0.23
Total weight for 4 clusters	1

Table A.2
Evaluation of the organizational criteria cluster for assessing the industrial safety management system at the enterprise (by points and weight).

Name of criterial parameter	1 score	2 scores	3 scores	4 scores	5 scores	Weight
Organization of training in industrial safety management,%	>90	90–70	70–60	60–50	<50	0.047
Functioning of the department (responsible person) for industrial and occupational safety at the enterprise [1)]	A2+B3 A3+B3	A3+B2 A2+B2	A1+B3A2+B1A3+B1	A1+B2	A1+B1	0.034
Availability of a full set of technical documentation, accounting logs, and cerificates, %	>90	90–70	70–60	60–50	<50	0.015
Periodic revision of instructions and schemes, periodicity	once a year	once every 2 years	once every 3 years	once every 5 years	not carried out	0.015
Completing written work procedures and tasks with clear instructions, %	>90	90–70	70–60	60–50	<50	0.065
Process hazard (risk) analysis (PHA) for process hazards identification, assessment, and control, number	0	1	2	3	more than 3	0.068
Application and verification of the state of systems of control equipment (CE) and automation equipment, number/%.	All systems are in operation	Missing 1 of the systems/ 90–70	Missing 2 of the systems/ 70–60	Missing 3 of the systems/ 60–50	Lack of all systems / <50	0.021
Periodic inspections of workplaces, compliance of equipment and construction with design specifications and industrial safety requirements,%	>90	90–70	70–60	60–50	<50	0.047
Monitoring the maintenance of the territory of the enterprise (site) in the	>90	90–70	70–60	60–50	<50	0.02

(*continued on next page*)

Table A.2 (*continued*)

Name of criterial parameter	1 score	2 scores	3 scores	4 scores	5 scores	Weight
proper order (accident-free condition), %						
Availability of staff feedback with management on process risk analysis and other process control elements. Availability of safety incentive programs	Yes	Constantly	Periodically	Particularly	No	0.056
Availability of a detailed contingency plan. Conducting training sessions [2)]	A1+B1+C1	A1+B2+C1, A1+B2+C2, A2+B1+C1	A1+B1+C2, A1+B3+C1, A2+B1+C2, A2+B2+C1	A1+B3+C2, A2+B2+C2, A2+B3+C1, A2+B3+C2	A3+B1+C1, A3+B1+C2, A3+B2+C1, A3+B2+C2, A3+B3+C1, A3+B3+C2	0.01
Periodic audit of industrial safety management	once a year	once every 2 years	once every 3 years	less than once every 3 years	not carried out	0.007
Maintenance of auxiliary systems (ventilation, heating, sewerage) at workplaces, sites, at the enterprise as a whole in the proper order	excellent	good	satisfactory	bad	none	0.025

Explanations for filling out the questionnaire on the cluster of organizational criteria for assessing the industrial safety management system at the enterprise.

[1)] - The functioning of the department (responsible person) for industrial and occupational safety at the enterprise:

A. Department Staffing, quantity: A1 - less than 75%, A2 - 75–100%, A3 –100 %;

B. Qualifications (work experience): B1, less than three years; B2 - to 3–5 years, B3, more than five years.

A combination of indicators A and B was selected. For example, A1 + B2.

[2)] - Availability of a detailed contingency plan: A1 - yes, A2 – outdated (overdue revision date), and A3 - no.

Availability of allocated and signed places of access, parking, and reversal of special equipment used to eliminate emergencies, in accordance with the accident response plan. Availability and condition: B1, good; B2, satisfactory; B3, absent.

Conducting training sessions on the actions of personnel in case of an emergency: C1 - periodic, C2 - absent.

A combination of three indicators (A, B, and C) was selected. For example, A1, B1, and C2.

Table A.3

Assessment matrix of the technical criteria cluster for assessing the industrial safety management system at the enterprise (according to the equipment used at the industrial enterprise) (by points and weight).

Name of criterial parameter	1 score	2 scores	3 scores	4 scores	5 scores	Weight
Pressurized vessels, group [1)]	not included	4	3	2	1	0.023
Separation equipment, m^3	<4	4–16	16–50	50–200	>200	0.014
Chemical reactors. Working volume, m^3	<0.5	0.5–1	1–10	10–50	>50	0.011
Heat exchange equipment. Heating surface square, m^2	<10	10–200	200–400	400–800	>800	0.011
Length of pipeline systems transporting HC, m	<50	50–100	100–150	150–250	>250	0.046
Wear coefficient of fixed assets, share [2)]	<0,01	0,01–0,03	0,03–0,05	0,05–0,1	>0,1	0.035
Replacement coefficient of fixed assets, share [3)]	>0,95	0,8–0,95	0,6–0,8	0,3–0,6	<0,3	0.025
Capacity of pumps (compressors), m^3/h	<50	50–100	100–200	200–1000	>1000	0.02
Number of storage tanks for CH at the site, pcs	1	2	3	4	>4	0.029
Controls (control devices, alarms, sensors, interlocks, availability of safety systems, including automatic shut-off valves) [4)]	Availability of all systems	Availability of 4 out of 5 systems	Availability of 3 out of 5 systems	Availability of 2 out of 5 systems	Availability less than 2 out of 5 systems	0.026
Availability of means of localization, systems and devices for release and ventilation [5)]	A+B+C+*D*	A+B+C, A+B+*D*, A+C + D, B+C+*D*	A+B, B+C, A+C, A+*D*, C + D, B+*D*	A, B, C, D	Absent	0.01

Explanations for completing the questionnaire on the cluster of technical criteria for assessing the industrial safety management system at the enterprise (according to the equipment used at the industrial enterprise).

[1)] - Pressurized vessels are classified in accordance with 'SR 03–576–03 2008 rules for the design and safe operation of pressurized vessels.'

[2)]- Wear coefficient of fixed assets is determined by the equation:

$$C_W = \frac{n_1}{(n_2)}, \text{(A.1)}$$

where n_1 is the number of technical devices that have worked out the established service life according to the results of the year.

n_2 is the total number of technical devices registered as fixed assets according to the results for the year.

[3)] - Replacement coefficient of fixed assets is determined by the equation:

$$C_F = \frac{n_3}{(n_1)}, \text{(A.2)}$$

where n_3 is the number of technical devices that worked out the established service life and were replaced during the reporting year.

If the number of technical devices that have worked out the established service life at the end of the year is zero, C_F is assumed to be zero.

[4)] - The presence of a system of controls at the main technological units is assessed:

Control devices, alarms, sensors, and blocking at loading points.

- Control devices, alarms, sensors, and blocking tanks.
- Control devices, alarms, sensors, and blocking pipelines.
- Control devices, alarms, sensors, and blocking separation equipment.
- Control devices, alarms, sensors, and blocking in pressurized vessels.

Note: If the production process does not have provisions for some of the listed systems of control, then by default, those systems are considered conditionally present.

This assessment is based on the presence (quantity) and functional readiness of systems (1, 2, 3, etc.).
[5)] - Availability of means of containment, systems and devices for discharge and ventilation.
A - physical barriers (pallets);
B - special sewerage;
C - reagents for neutralization;
D - technological possibility of emergency releases.
Note: If the production process does not have provisions for some of the listed containment devices or the presence of an automatic shut-off valve, then the containment tools or automatic shut-off valves are considered conditionally available by default.
The assessment is based on the presence (number and combination) and functional readiness of these systems. A combination of four indicators (A, B, C, and D) was selected.

Table A.4
Evaluation matrix of human (personnel working at an industrial enterprise) criteria cluster for assessing the industrial safety management system at an enterprise (by points and weight).

Name of criterial parameter	1 score	2 scores	3 scores	4 scores	5 scores	Weight
Assessment of the level of knowledge of personnel of safety rules and industrial instructions,%	>90	90–70	70–60	60–50	<50	0.034
Conformity of knowledge of contractors with safety rules and production process,%	>95	95–90	90–85	85–80	<80	0.01
Staffing of brigades,%	>95	95–90	90–85	85–80	<80	0.031
Schedule of the labor process [1)]	A		B		C	0.015

Explanations for completing the questionnaire on the cluster of human (personnel working in an industrial enterprise) criteria for assessing the industrial safety management system at an enterprise:
[1)] - Schedule of the labor process:
The A-Technological process at CHS was carried out only during the day shift.
B - Technological process at the CHS is carried out in 2 shifts;
C - Technological process at the CHS is carried out in 3 shifts.
The assessment was performed by selecting one of the following options: A, B, or C.

Table A.5
Evaluation matrix of the technological (design) criterial cluster for assessing the industrial safety management system at the enterprise, considering the HC used in the technological process (by points and weight).

Name of criterial parameter	1 score	2 scores	3 scores	4 scores	5 scores	Weight
Functioning of the Change Process Management System, year [1)]	<1	1–3	3–5	5–10	>10	0.038
Compliance with the design solutions of buildings and constructions, warehouses, places of storage of hazardous chemicals,%	>95	95–90	90–85	85–80	<80	0.023
Compliance with the design solutions of protective and safety devices, control equipment,%	>95	95–90	90–85	85–80	<80	0.016
Compliance with the design of ventilation, heating, sewerage, plumbing, lighting systems at workplaces, sites, the enterprise as a whole,%	>95	95–90	90–85	85–80	<80	0.017
Compliance with the design of the operation of processing lines and new equipment, %	>95	95–90	90–85	85–80	<80	0.021
Data on corrosivity [2)]	Low 1		Medium 2		High 3	0.013
Storage volume, t For instance: Ammonia Chlorine Sulphur dioxide Sulpuric acid	Less, then lower-tier establish-ment value < 50 < 10 < 10 < 50		Higher, then lower-tier establish-ment value and less then upper-tier establish-ment value 50 – 200 10 – 25 10 – 25 50 – 200		Higher, then upper-tier establishment value > 200 > 25 > 25 > 200	0.024
Hazard classes of chemical products [3)], which are:						0.015
- flammable liquid	5	4	3	2	1	
- flammable solid		2		1		
- flammable gas				1		
Hazard classes of explosive chemical products [4)]	1.6	1.5	1.4, 1.3	1.2	1.1	0.02
Temperature class (Autoignition temperature of the mixture, °C) [5)]	T1 >450	T2 300 - 450	T3 200 - 300	T4 135 - 200	T5, T6 135–85	0.01
Combustibility group [6)]		hardly combustible			combustible	0.013

Explanations on filling out the questionnaire on the cluster of technological (design) criteria parameters for assessing the industrial safety management system at the enterprise, considering the HC used in the technological process:
[1)] - Functioning of the change process management system (chemicals processing, changes in company technology, changes in equipment, changes in company

procedures, changes in facilities). It is estimated as the frequency of considering the possibility of changes in order to move toward improved labor safety and less hazardous technological solutions.
2) - It is filled according to the interstate standard ‘OSSS GOST 19,433–88 dangerous goods. classification and labeling.’
3) - It is filled according to ‘GOST 32,419–2013 hazard classification of chemical products.’.
4)- Hazard classes of explosive chemical products are determined in accordance with ‘GOST 32,419–2013 hazard classification of chemical products.’.
5)- The temperature class is determined according to the ‘interstate standard OSSS GOST 31,610.20–1–2020 explosive atmospheres - Part 20–1: material characteristics for gas and vapor classification - test methods and data.’
6) The combustibility group was determined according to the ‘interstate standard SSBT GOST 12.1.044–89 fire and explosion hazard of substances and materials. nomenclature of indices and methods of their determination.’

Table A.6
Evaluation matrix of the vulnerability index cluster of the working personnel of an industrial enterprise from a chemically hazardous site (by points and weight).

Name of criterial parameter	1 score	2 scores	3 scores	4 scores	5 scores	Weight
Availability of time for evacuation and other emergency measures in the case of an accident 1)	A1	A2	A3	A4	A5	0.4
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 hardware room 2)	A1	A2	A3	A4	A5	0.1
Presence of protective structures 3)	A1	A2	A3	A4	A5	0.1
Presence of identification marks, fences, light signaling, removable lockable shields, warning alarms, warning posters 4)	A1	A2	A3	A4	A5	0.03
Presence of systems of aspiration, ventilation, dust suppression, disposal and localization of harmful substances 5)	A1	A2	A3	A4	A5	0.07
Presence of remote devices and controls, control systems, providing protection against self-starting, round-the-clock surveillance 6)	A1	A2	A3	A4	A5	0.05
Presence of protectors 7)	A1	A2	A3	A4	A5	0.05
Presence of local ventilation systems, local suction systems, individual sewerage, water supply and protective devices 8)	A1	A2	A3	A4	A5	0.09
State of personal protective equipment 9)	A1	A2	A3	A4	A5	0.05
Staffing of the enterprise personnel with personal protective equipment 10)	A1	A2	A3	A4	A5	0,06

Explanations for completing the questionnaire on the cluster of the vulnerability index of the working personnel of an industrial enterprise from a chemically hazardous site.
1) In the case of an emergency, the percentage of operating personnel with sufficient time to evacuate from the danger zone is estimated. One of the options is selected: A1 - 100 %, A2 - more than 80 %, A3 - in the range from 70 to 80 %, A4 - in the range from 50 to 70 %, A5 - less than 50 %.
2) Availability of an evacuation plan for the CHS personnel of the enterprise in the case of equipment failure or an emergency and the presence of evacuation exits in the premises of the engine and hardware rooms. One option was selected as follows:.
A1: Availability of an evacuation plan for the CHS personnel of the enterprise in the case of equipment failure or an emergency and the presence of at least two evacuation exits in the premises of the engine room and hardware room.
A2 - Availability of an evacuation plan for the CHS personnel of the enterprise in the case of equipment failure or an emergency and the presence of less than two emergency exits in the premises of the engine and hardware rooms.
A3 - Availability of an evacuation plan for the personnel of the enterprise CHS in the case of equipment failure or an emergency, and the absence of evacuation exits in the premises of the engine and equipment rooms.
A4: Lack of an evacuation plan for the personnel of the enterprise CHS in case of equipment failure or an emergency. Evacuation exists in the premises of the engine room and equipment room.
A5: Absence of an evacuation plan for the personnel of the enterprise CHS in case of equipment failure or an emergency. Absence of emergency exits on the engine and equipment rooms.
3) The effectiveness of existing protective structures against the impact of destructive factors on working personnel was assessed. One of the options is selected: A1 - 100 %, A2 - more than 80 %, A3 - in the range from 50 to 80 %, A4 - less than 50 %, A5 - absent.
4) The completeness of the auxiliary equipment was assessed. One of the options is selected: A1 - 100 %, A2 - more than 80 %, A3 - in the range from 50 to 80 %, A4 - less than 50 %, A5 - absent.
5) System conditions were assessed. One of the following options was selected: A1, excellent; A2, good; A3, satisfactory; A4, poor; and A5, absent.
6) Availability of remote instruments and controls, control systems, provision of protection against self-start, round-the-clock monitoring, considering the specifics of the production process (equipment of the electrolysis unit with control systems when chlorine is used in the technological process, presence of an external circuit chlorine leak control with an alarm, equipped with ammonia compressors with emergency protection equipment, temperature protection, presence of signaling devices for the concentration of ammonia vapors, and automatic control of the pH of heated water). The presence and conditions of these systems were assessed. One of the options is selected: A1 - 100 %, A2 - more than 80 %, A3 - in the range from 50 to 80 %, A4 - less than 50 %, A5 - absent.
7) Availability of protectors (availability of water seals to turn off the equipment on the furnace gas line in the technological processing of phosphorus; equipping pallets and platforms with boards). The presence and condition of safety devices were assessed. One of the options is selected: A1 - 100 %, A2 - more than 80 %, A3 - in the range from 50 to 80 %, A4 - less than 50 %, A5 - absent.
Note: If the presence of any of the listed protective structures and other means of collective protection in the technological process is not provided by the specifics of production, then by default, this system is considered conditionally available.
8) The staffing and performance of local systems were assessed. One of the options is selected: A1 - 100 %, A2 - more than 80 %, A3 - in the range from 50 to 80 %, A4 - less than 50 %, A5 - absent.
9) Technical conditions of PPE in the workplace were assessed. One of the following options was selected: A1, excellent; A2, good; A3, satisfactory; A4, poor; and A5, absent.
10) The provision of personnel with PPE to the enterprise with PPE is assessed. One of the options is selected: A1 - 100 %, A2 - more than 80 %, A3 - in the range from 50 to 80 %, A4 - less than 50 %, A5 - absent.

Appendix B

Table B1
Scoring of criterial parameters as a result of a survey of employees of industrial enterprises with industrial enterprises of the Republic of Kazakhstan a survey of employees of industrial enterprises with CHS of the Republic of Kazakhstan.

No.	Enterprise (workshop)* Name of criterial parameter	1	2	3	4	5	6	7	8	9	10	11	12	13
Cluster of *Organizational Criterial Parameters for Assessing the Industrial Safety Management System at the Enterprise*														
1	Organization of training in industrial safety management	1	1	1	1	1	1	1	1	1	1	1	1	1
2	Functioning of the department (responsible person) for industrial and occupational safety at the enterprise	1	1	1	1	1	1	4	4	4	2	2	2	3
3	Availability of a full set of technical documentation, accounting logs, and cerificates	1	1	1	1	1	1	1	1	1	1	1	1	1
4	Periodic revision of instructions and schemes, periodicity	1	3	3	3	3	3	1	1	1	3	3	3	4
5	Completing written work procedures and tasks with clear instructions	1	1	1	1	1	1	1	1	1	1	1	1	1
6	Process hazard (risk) analysis (PHA) for process hazards identification, assessment, and control	5	3	4	3	4	3	5	5	5	4	4	4	4
7	Application and verification of the state of systems of control equipment (CE) and automation equipment	1	1	1	1	1	1	1	1	1	1	1	1	1
8	Periodic inspections of workplaces, compliance of equipment and construction with design specifications and industrial safety requirements	1	1	1	1	1	1	1	1	1	1	1	1	1
9	Monitoring the maintenance of the territory of the enterprise (site) in the proper order (accident-free condition)	1	1	1	1	1	1	1	1	1	1	1	1	2
10	Availability of staff feedback with management on process risk analysis and other process control elements. Availability of safety incentive programs	1	1	1	1	1	1	1	1	1	1	1	1	1
11	Availability of a detailed contingency plan. Conducting training sessions	1	1	1	1	1	1	1	1	1	1	1	1	1
12	Periodic audit of industrial safety management	1	1	1	1	1	1	1	1	1	1	1	1	5
13	Maintenance of auxiliary systems (ventilation, heating, sewerage) at workplaces, sites, at the enterprise as a whole in the proper order	2	2	2	3	3	3	2	2	2	3	3	3	3
Cluster of *Technical Criterial Parameters for Assessing the Industrial Safety Management System at the Enterprise (for the equipment used at the enterprise)*														
1	Pressurized vessels	4	2	5	0	5	0	5	5	5	4	2	3	4
2	Separation equipment	0	0	4	0	5	0	0	0	0	4	4	2	0
3	Chemical reactors. Working volume, m^3	1	4	5	5	5	5	4	5	5	5	5	0	0
4	Heat exchange equipment. Heating surface square, m^2	0	4	4	2	5	1	4	5	5	5	2	0	2
5	Length of pipeline systems transporting HC, m	5	4	3	5	5	5	5	5	5	5	5	2	5
6	Wear coefficient of fixed assets, share	1	1	1	5	5	4	5	5	5	5	5	5	4
7	Replacement coefficient of fixed assets, share	1	1	1	4	4	1	4	4	4	5	4	1	1
8	Capacity of pumps (compressors), m^3/h	4	1	5	5	3	5	3	4	4	5	5	5	0
9	Number of storage tanks for CH at the site, pcs	5	5	4	5	5	2	5	5	0	3	5	0	5
10	Controls (control devices, alarms, sensors, interlocks, availability of safety systems, including automatic shut-off valves)	1	1	1	2	5	1	1	5	5	1	1	1	1
11	Availability of means of localization, systems and devices for release and ventilation	1	1	1	3	5	1	1	5	5	1	1	1	1
Cluster of *Human* (personnel working at an industrial enterprise) *Criterial Parameters for Assessing the Industrial Safety Management System at an Enterprise*														
1	Assessment of the level of knowledge of personnel of safety rules and industrial instructions	1	1	1	2	1	1	1	1	1	1	1	1	1
2	Conformity of knowledge of contractors with safety rules and production process	1	1	1	5	1	1	1	1	1	5	3	0	5
3	Staffing of brigades	1	2	3	2	1	4	1	1	1	2	4	4	1
4	Schedule of the labor process	5	5	5	3	5	5	5	5	5	3	3	3	3
Cluster of *Technological* (project) *Criterial Parameters for Assessing the Industrial Safety Management System at the Enterprise, Taking into Account the HC Used in the Technological Process*														
1	Functioning of the change process management system	5	2	2	5	1	1	1	1	1	5	5	1	5
2	Compliance with the design solutions of buildings and constructions, warehouses, places of storage of hazardous chemicals	1	1	1	1	1	1	1	1	1	1	1	1	1
3	Compliance with the design solutions of protective and safety devices, control equipment	1	1	1	2	1	1	1	1	1	1	1	5	1
4	Compliance with the design of ventilation, heating, sewerage, plumbing, lighting systems at workplaces, sites, the enterprise as a whole	5	1	1	1	4	1	1	1	1	1	1	1	1
5	Compliance with the design of the operation of processing lines and new equipment	1	1	1	1	1	1	1	1	1	1	1	1	1
6	Data on corrosivity	5	1	5	5	5	5	3	5	5	5	5	1	5
7	Storage volume	5	1	5	1	5	1	5	5	0	5	5	0	5
8	Hazard classes of chemical products	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Hazard classes of explosive chemical products	0	4	0	0	0	0	0	0	0	0	0	0	0

(*continued on next page*)

Table B1 (*continued*)

No.	Enterprise (workshop)* Name of criterial parameter	1	2	3	4	5	6	7	8	9	10	11	12	13
10	Temperature class (Autoignition temperature of the mixture, °C)	1	1	1	1	1	1	1	1	1	1	1	1	1
11	Combustibility group	0	0	0	0	0	0	0	0	0	0	0	0	0
Cluster of *Criterial Parameters for Assessing the Vulnerability (index) of Working Personnel under the Influence of a Destructive Factor as a Result of Man-made Emergencies at a Chemically Hazardous Site*														
1	Availability of time for evacuation and other emergency measures in the case of an accident	1	1	1	1	1	1	2	1	1	1	1	1	1
2	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 hardware room	1	1	1	1	1	1	1	1	1	1	2	1	1
3	Presence of protective structures	1	1	1	1	1	1	1	1	1	1	2	1	1
4	Presence of identification marks, fences, light signaling, removable lockable shields, warning alarms, warning posters	2	1	1	1	3	1	1	1	1	1	2	1	1
5	Presence of systems of aspiration, ventilation, dust suppression, disposal and localization of harmful substances	1	1	1	1	1	2	2	2	2	1	2	1	2
6	Presence of remote devices and controls, control systems, providing protection against self-starting, round-the-clock surveillance	1	1	1	1	2	2	1	1	1	1	2	1	2
7	Presence of protectors	1	1	1	1	1	1	1	1	1	1	1	1	1
8	Presence of local ventilation systems, local suction systems, individual sewerage, water supply and protective devices	3	2	2	3	2	5	2	2	2	1	1	1	1
9	Presence of personal protective equipment in the workplace	2	1	1	1	1	1	1	1	1	1	2	1	1
10	Staffing of the enterprise personnel with personal protective equipment	1	1	1	1	1	1	1	1	1	1	1	1	1
Cluster of *Criterial Parameters for Assessing the Risk of Occupational Injury to the Working Personnel of an Industrial Enterprise from a Chemically Hazardous Site*														
1	Number of work-related injuries at enterprise (or in its subdivisions) for the study period	0	0	0	1	1	5	0	1	1	1	4	0	2
2	Average number of employees at enterprise (or in its subdivisions) for the study period	1170	218	263	676	202	506	132	75	258	110	450	135	490
3	The degree of long-term disability of workers as a result of work-related injuries received during the study period	–	–	–	15 %	fatal	20 %	–	20	60	fatal	15 %, 60 %, 50 %, and fatal	–	15 %, 50 %
Cluster of *Criterial Parameters for Assessing the Risk of Developing Occupational Diseases among the Working Personnel of an Industrial Enterprise from a Chemically Hazardous Site*														
1	Number of workplaces (WP) at the industrial site in the *i* th class of labor conditions	3.1-2 WP	3.1-37 WP	3.1-22 WP	3.1 – 57 WP	3.1 - 50 WP	3.1 - 77 WP	2	2	2	3.1 - 55 WP	3.1 - 60 WP	3.1 - 67 WP	2
2	The total number of workplaces in the industrial site	36	102	147	310	70	202	38	23	59	110	450	135	200
3	Number of employees of the industrial site with newly diagnosed occupational diseases	0	0	0	0	0	1	0	0	0	0	1	0	0
4	Total number of employees at the industrial site	1170	218	263	676	202	506	132	75	258	110	450	135	490

List of industrial enterprises (workshops) with CHS for which the survey was conducted *.
1 – *Kainar* LLP, Taldykorgan;.
2 - Workhop of precious metals, *Kazakhmys Smelting* LLP, Balkhash;.
3 – Workhop of sulphuric acid, *Kazakhmys Smelting* LLP, Balkhash;.
4 - Workhop of copper electrolysis, *Kazakhmys Smelting* LLP, Balkhash;.
5 - Workhop of sulphuric acid, *Kazakhmys Smelting* LLP, Zhezkazgan;.
6 - Workhop of copper electrolysis, *Kazakhmys Smelting* LLP, Zhezkazgan;.
7 – Ammonia production workshop, *KazAzot* JSC, Aktau;.
8 - Workshop of weak nitric acid, *KazAzot* JSC, Aktau;.
9 - Workshop for the production of complex mineral fertilizers, *KazAzot* JSC, Aktau;.
10 - Workhop of sulphuric acid, *Mineral Fertilizers* factory of *Kazphosphate* LLP, Taraz;.
11 – Workshop of ammophos, *Mineral Fertilizers* factory of *Kazphosphate* LLP, Taraz;.
12 - Workshop for the production of fodder defluorinated phosphates, *Mineral Fertilizers* factory of *Kazphosphate* LLP, Taraz;.
13 - *Kaustik* LLP, Pavlodar.’.

Table B1

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