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An Expert Approach to Assessing Technogenic Risk at Enrichment Plants

Gulmira S. Sattarova[1], Yelena A. Tseshkovskaya[1], Natalya K. Tsoy[1], Firuza K. Batessova[2*], Vladlena S. Shevtsova[2]

[1] Department of Mine Aerology and Occupational Safety, Abylkas Saginov Karaganda Technical University, Karaganda 100027, Kazakhstan
[2] Department of Engineering Systems and Networks, Satbayev University, Almaty 50013, Kazakhstan

Corresponding Author Email: firuza_78@mail.ru

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ABSTRACT

This article presents a methodological approach to the assessment of technogenic risk based on expert assessments in the processing plants of Central Kazakhstan. During the expert study, the criteria were determined by which the composition of the expert group was formed, and special linguistic scales were developed to carry out the procedure for assessing risk indicators by experts. Expert studies were conducted on 10 possible types of accidents at enrichment plants in Central Kazakhstan. The assessment of the consistency of expert opinions was carried out using the Kendall concordance coefficient. As a new approach for assessing technogenic risk, technical and ecological criteria were identified and their influence on the probability and consequences of accidents was assessed. These parameters formed the basis for multifactorial mathematical models of hazard indicators and the severity of the consequences of an accident during ore processing and enrichment. Scales have been developed to assess the hazard and severity of accidents, a risk assessment matrix, as well as a description of accident risk levels. Corrective measures for enrichment plants have been proposed. This technique is applicable to various production processes.

1. INTRODUCTION

An enrichment plant is an intermediate link between a mine and a metallurgical plant that processes factory concentrates, which contain more valuable product than the feedstock. When processing mineral raw materials in order to obtain a technically valuable product suitable for industrial use, various technological processes are used. In this case, hazardous flammable substances and technological devices operating under a pressure of more than 0.07 MPa are used, as well as permanently installed lifting mechanisms. According to the Law of the Republic of Kazakhstan "On Civil Protection" [1], enrichment plants are classified as hazardous production facilities. According to the Environmental Code of the Republic of Kazakhstan [2], enrichment plants are classified as I category facilities that have a significant negative impact on the environment.

Depending on the processing method, the technological scheme of an enrichment plant includes such processes as crushing and grinding, flotation, electromagnetic and magnetic separation, thickening and dewatering, heap leaching, ore cyanidation, agglomeration, roasting and drying, washing, etc. This article presents research results based on the example of ore enrichment plants using the flotation method. The technological scheme at these facilities provides for crushing in jaw and cone crushers, fine crushing and softening in high-pressure crushers, ball crushing, main, control and peristory flotation, concentrate grinding, concentrate thickening and filtration, tailings thickening, preparation and dosing of reagents.

Accidents are possible during the processing of flotation ore. The consequences of accidents can be catastrophic with injury and death of people, flooding of lands, groundwater and surface waters and atmospheric air. The elimination of such accidents is usually associated with the shutdown of production, expensive work on the restoration of technological equipment and cleaning of contaminated areas.

For example, Lonsk and Liskova [3], when analyzing accidents at crushing and screening factories of quarries, note a high level of severe and fatal industrial injuries. At the same time, up to 90% of injuries and accidents occur due to improper actions of personnel. The lack of reliable information about hazards at enrichment plants does not allow reliable forecasting and timely prevention of the occurrence and development of hazardous production situations. An information source [4] reports on an accident at the Stoilensky plant (Russia), which led to a production shutdown. Repair work was carried out 24 hours per day for 12 days. 10 spread to the waters of the Tikhaya and Ulba rivers [5]. According to the results of the audit of the environmental prosecutor's office of the East Kazakhstan region, it was revealed that the damage from the incident exceeded 11.5 million dollars. The information source contains information about an accident that occurred at one of the tailings dumps of the Vale Corporation of the Corrego de Feijao iron ore enterprise (Brazil) on January 25, 2019 [6]. Due to the downpours, a catastrophic dam burst occurred. The work of the enterprise was stopped. Timofeeva et al. [7] conducted an assessment of occupational risks at the Chadak gold recovery plant (Uzbekistan), which carries out the enrichment and extraction of gold from ore using cyanide solutions. Based on the results of the risk assessment, it was found that a significant part of the work performed at the factory is classified as a high risk category. Abandoned tailings dumps pose a separate serious danger to the environment and society as a whole. Possible threats include contamination of water and soil resources with toxic substances, the risk of collapse of structures, fire or the release of harmful gases. For example, Kovlekov et al. [8] raise the problem of abandoned tailings dumps after the closure of mining and processing plants in Russia and describe in their article the catastrophic consequences of accidents that occurred at tailings dumps in Brazil (2015), Hungary (2010) and Russia (2009).

Glotov et al. [9] assessed the geoecological condition of the abandoned tailings dump of the former Karamken Mining and Metallurgical Plant (Russia), where flood waters broke through. The accident led to a salvo release of a mudflow mass, which caused the partial destruction of a residential settlement, the death of 2 people and the destruction of river hydrobionts. In the scientific work, Sherhov and Gergokova [10] analyzed the state of hydraulic structures at the tailings dam of the Tyrnyauzsky GOK (Russia), which does not have an owner and a specialized supervising organization. A comparative analysis of the data obtained during the processing of survey materials shows a steady increase in the risks of catastrophic events at this facility. To ensure industrial and environmental safety Ryzhkov et al. [11] propose measures for decommissioning and transferring the tailings dump of a coal processing plant to conservation with its subsequent liquidation. Ozhigin et al. [12] propose a method for assessing the stability of quarry slopes for early detection of emergency situations. Using the parameters used in the methodology, it is possible to monitor the condition of tailings dumps and prevent spills and leaks of chemical substances. Solving issues of ensuring industrial and environmental safety at enrichment plants is directly related to the analysis and assessment of the risk of accidents at all stages of the production process. This is the only way to assess the likelihood of negative events occurring and their consequences and develop effective and efficient measures to improve labor safety, health and environmental protection.

The authors of this article chose the method of expert assessments to assess the risk of accidents at an enrichment plant. This method is less sensitive to the inaccuracy and vagueness of the initial data, and makes it possible to simultaneously take into account dozens of disparate parameters, which makes it possible to take into account the specifics and complexity of the technological processes of mineral processing and the technical features of the equipment. Intuitive characteristics based on the knowledge and professional experience of the expert provide, in some cases, fairly accurate estimates. Expert methods quickly and without much time and labor provide information about criterion parameters and their values.

The article presents the results of research on assessing the technogenic risk of accidents at enrichment plants using an expert approach. The use of expert assessments makes it possible to summarize expert opinions about the possibilities (or probabilities) of accidents occurring and the consequences of its impact on the environment, as well as to develop criteria parameters and determine their hierarchical structure for the development of multifactor models of indicators of danger and severity of accidents. The object of the study is the process of ore processing by flotation.

Based on the results of the analysis, a methodology was developed for conducting an expert study to determine technical and environmental criteria for risk assessment, a procedure for creating multifactor models of the components of accident risk, linguistic scales for implementing the procedure for assessing risk indicators, and a matrix was proposed for assessing the risk of accidents at enrichment plants. The article provides an example of calculating the risk assessment of an accident – a rupture of a slurry pipeline at an enrichment plant.

2. LITERATURE REVIEW

Scientists use various methods of risk assessment in the field of industrial safety, based on qualitative and quantitative approaches to hazard assessment. The quantitative methods are based on the objective measurement and prediction of the consequences of the realization of the danger. They involve the calculation of risk indicators and are more accurate. For example, in research on risk assessment, scientists use hierarchy analysis methods (HAM), which allow mathematically modeling the decision-making process based on initial information and solving multi-criteria problems.

In particular, Dai et al. [13] have developed a system for assessing the stability of a tailings dam using the hierarchy analysis methods (HAM) from four aspects, such as design and construction, natural environment, operational sustainability and management. The combination of the hierarchy analysis process with the cloud model method made it possible to obtain a comprehensive assessment of the state of China's uranium tailings dumps. Silvestri et al. [14] propose a new methodological approach for risk assessment, which uses analyzing the types and consequences of failures methods, taking into account the economic costs of safety.

In addition, scientists determine the index of the total risk priorities number (TRPN), which is based on the improved risk priorities number (IRPN) and the analytical network process (ANP), a multi-criteria decision-making method. In their publication [15], the authors use an interpreted structural model (ISM) for a comprehensive analysis of the structural relationship of the main risk factors causing accidents in uranium tailings dumps. ISM as a method of system engineering analysis allowed us to find out the structure of factors in the system that affect environmental safety. Other scientists use a combination of two methods to evaluate the response system to man-made emergencies: multilevel flow modeling (MFM) for developing intellectual judgments and Go-Flow for quantifying risk and building a risk matrix [16]. This approach is considered on the example of the Fukushima nuclear power plant. In the scientific work [17], scientists developed a comprehensive risk assessment method based on the theory of disasters, which was used to analyze the risk levels of ten large chemical enterprises. In the articles [18-21], Bayesian networks are used by scientists to model various situations, study the causal relationships of accident factors and conduct probabilistic analysis, allowing them to predict possible scenarios for the development of complex processes and their catastrophic consequences. Lisanov et al. [22] apply probabilistic estimates in analyzing safety at hazardous production facilities and quantifying the risk of accidents. In security theory, a variety of logical and probabilistic models based on methods such as the "failure tree" - "event tree" are widely used to assess probability. These methods allow us to quantify the risk in a deductive way. The Event Tree Analysis (ETA) method is used to estimate the frequency of intermediate (initiating and subsequent) events in the analyzed accident scenarios. In the scientific publication [23], the authors use logical event trees to analyze the impact of initiating events and identify possible scenarios for the development of an accident and determine the consequences of each scenario for explosive and flammable objects. In their study [24], the authors used the HAZOP method, which made it possible to determine the roles of various components of the technical system.

At the same time, the analysis was supplemented by the use of the event and failure tree method to quantify the probability of malfunction of the specified system. To dynamically update the probability of key variables, Chen et al. [25] propose a new method based on Bayesian theory. Based on the dynamic probability of key process variables, event trees of possible consequences caused by variable anomalies are constructed. The probability of various consequences can be obtained from the logical relationships of the event tree. The "Failure Tree Analysis" method is used to analyze the most likely causes of an accident and calculate its frequency. The article [26] presents the features of the method of analyzing the call tree as a tool to improve the efficiency of safety management in an enterprise. The causal relationships between events in the failure tree scheme are considered using individual examples.

It can be seen from the analyzed articles that quantitative methods require a large amount of information about technological processes and equipment, the state of industrial safety, the location and time of stay of people on the territory of the facility and other factors for calculations. Highly qualified specialists may be required to perform calculations. These shortcomings of quantitative methods can complicate the risk assessment process and affect the objectivity of the results. High-quality methods require less data and labor. These methods are recommended to be used at the stage of hazard identification, so they usually precede quantitative ones. The largest volume of proposals for ensuring the safety of hazardous production facilities is formed using qualitative risk analysis methods. As a rule, a qualitative risk assessment is carried out with the help of experts in a particular industry. These include expert assessment methods, the scoring method, checklists, “brainstorming”, “matrix method”, “bow tie”, HAZOP, Delphi method and others. Qualitative methods do not provide for the use of any rigorous mathematical models and immediately display the result of a "risk assessment". For example, in scientific papers [27-30], the authors, using qualitative methods, determine the consequence, possibility and level of risk according to descriptive scales, combine consequence and possibility, and evaluate the resulting risk in accordance with qualitative criteria. When choosing a risk assessment method, it is necessary to be guided by the degree of certainty. It is possible to use computational and graphical methods with full certainty, use probabilistic and statistical methods with average certainty, and use expert estimates with complete uncertainty.

As practice shows, in general, there is a lack of information about accidents at hazardous production facilities, including processing plants, which makes it difficult to conduct a qualitative statistical analysis. A sample of statistical data on accidents is usually not representative, i.e. does not allow drawing conclusions about the entire set of data, relying only on information about part of the totality. In the study of objects with uncertain parameters or unexplored properties, in conditions of insufficient volume or lack of statistical information, the experience and knowledge of experts are used. Expert assessment methods are widely used today. For example, Kachesova and Nikol’skii [31] have developed an expert system for assessing technogenic risks of electrical installations using time logic, which provides an adequate assessment of the technogenic safety of the considered production facility. In their works, Kurakina and Ivlichev [32] and Muzalevsky et al. [33] apply expert opinions to assess environmental risks. Other scientists use expert methods to assess the risk of accidents at hazardous production facilities and installations [34-36].

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Based on the results of the analysis, a methodology was developed for conducting an expert study to determine technical and environmental criteria for risk assessment, a procedure for creating multifactor models of the components of accident risk, linguistic scales for implementing the procedure for assessing risk indicators, and a matrix was proposed for assessing the risk of accidents at enrichment plants. The article provides an example of calculating the risk assessment of an accident – a rupture of a slurry pipeline at an enrichment plant.

3. RESEARCH MATERIAL AND METHODS

An enrichment plant is a complex production system with many technological and technical parameters. Identification and analysis of sources of danger, their damaging factors, determination of a list of possible accidents, a list of criterion parameters and their values is work with a large amount of technical information. In this case, it is necessary to take into account the interrelationship of the constituent elements of the production system, their properties and processes. Therefore, the research used a systematic approach to analyze and systematize initial information to assess the risk of accidents at enrichment plants.

When assessing risk, criteria parameters that have qualitative characteristics are used. The presence of qualitative valuescauses difficulties in their measurement and evaluation. To display their content and structure in a symbolic form using a mathematical language, a data formalization method was used, which allows transformations from verbal parameters to quantitative ones.

To determine the degree of influence of technical and environmental criteria on the probability and consequences of an accident, expert studies were carried out. The formation of the expert group was carried out on the basis of the documentary selection method. The criteria for the selection of experts were adopted:

1) competence (higher technical education; academic degree; academic title; certificate of advanced training; experience and skills in solving similar tasks; experience in participating in examinations);

2) work experience at a production facility (at least 7 years; or senior position);

3) attitude to the examination process (interest in research; active approach to conducting research; offer creative ideas; participate in public hearings in the field of industrial and environmental safety);

4) scientific potential (head or executor of scientific projects; publication activity; availability of copyright certificates or patents; membership in scientific communities; state awards for scientific developments);

5) absence of violations of labor protection, industrial and environmental safety requirements;

6) work experience in the field of environmental and industrial safety in (government agencies; non-governmental organizations).

Each value of the criterion was assigned 1 point, respectively, the maximum number of points a candidate can have is 20. An applicant who scores 15 or more points is included in the expert group.

When creating the expert group, a preliminary list of candidates was first formed using the classic "snowball" method. The final list of experts was formed taking into account the criteria described above, characterizing the level of competence, professional skills, work experience and personal qualities. When determining the number of experts, the opinions of experts in the field of expert assessments were taken into account. The number of experts in the group may depend on the specific task or area of expertise they are working on, as well as on the goals and requirements of the project. Experts believe that too few experts lead to an unreliable group assessment, and too many lead to the complexity of organizing an expert survey and forming a consensus on the issue under study.

Thus, according to Margolin E., the number of experts should not be less than the number of estimated factors or objects [37]. Based on the results of practical activities, Zernyi I.V. and others [38] recommend the most acceptable number of experts to be at least 7 and no more than 20 people. Zhukov B.M., Tkacheva E.N. in their works adhere to the limits from 10 to 30 experiments [39]. Petrov A.Iu. determined that with an acceptable error of expert analysis of 5%, the working group should include at least 6 experts [40]. For their research, Barkova D.V. and others formed an expert group of 20 specialists familiar with the state of affairs at thermal power plants. The results of the assessment of their competence showed that only 4 people (20% of the total) have a high level of competence [41].

For this study, 10 experts were selected for each type of accident. This numerical composition of the expert group corresponds to the opinions of experts in the field of expert assessments. The experts included leading specialists working at enrichment plants (chief engineers, technologists, mechanics, power engineers, site managers, environmental engineers), as well as representatives of government agencies and non-governmental organizations in the field of industrial and environmental safety. In the course of the expert study, specially designed questionnaires containing a list of questions on the degree of influence of criteria parameters on the probability of an accident and its consequences were used to obtain the individual opinion of the members of the expert group.

To fill out the questionnaires, experts used a scoring system in the form of a universal linguistic scale from 1 to 9, which is presented in Table 1. The use of a special scale allows you to convert qualitative values of parameters into quantitative ones and evaluate the role of each parameter in the formation of an indicator of the danger and severity of an accident. When processing the questionnaire data, the degree of agreement between the opinions of the experts who took part in the survey was assessed using a special measure - the Kendall concordance coefficient, which is determined by the following formula:

$$W = \frac{12 \times S}{n^2 \times (m^3 - m)} \tag{1}$$

where, S is the sum of squared deviations of all rank estimates for each object of examination from the average value; n is number of experts; m is number of objects of examination.

The concordance coefficient usually varies in the range $0<W<1$. Moreover, if $W=0$, then this is a complete inconsistency of expert opinions, if $W<0.3$ - unsatisfactory, if $0.3<W<0.7$ - average, with $W>0.7$ - high, with $W=1$ - complete unanimity [42].

Table 1. Scale for assessing the significance (degree of influence) of the criterion parameter

Degree of Influence	Assessment Linguistic	Points
Weak	A very weak degree of influence on the occurrence/severity of the accident	1
	A weak degree of influence on the occurrence/severity of the accident	2
	Insignificant degree of influence on the occurrence/severity of the accident	3
Average	Below the average degree of influence on the occurrence/severity of an accident	4
	The average degree of influence on the occurrence/severity of the accident	5
	Above the average degree of influence on the occurrence/severity of an accident	6
Strong	A significant degree of influence on the occurrence/severity of the accident	7
	A strong degree of influence on the occurrence/severity of the accident	8
	A very strong degree of influence on the occurrence/severity of the accident	9

The selected research methods allow us to solve the problems posed in the scientific work and obtain reliable risk assessment results. Risk assessment in accordance with the standards in the field of risk management [43, 44] is carried out in the following stages: identification of hazards; analysis of the probability of an accident and consequences; risk assessment. According to the standard stages of risk assessment, a methodology for assessing the risk of accidents has been developed, taking into account the features of the technological process of the flotation enrichment plant. The results of assessing the risk of accidents using the developed methodology are below.

4. HAZARD IDENTIFICATION

At the first stage of risk assessment, the structure of the enrichment plant, its main, auxiliary and service units were studied to identify hazards. The main production units at factories that process ore by flotation include: medium and fine crushing; fine crushing; grinding in ball mills; flotation (main, control and cleaning). Auxiliary areas include areas that ensure the uninterrupted flow of the main production process and the mutual coordination of all operations to prepare ore for its enrichment and carry out: thickening of ore concentrate; dehydration of ore concentrate; preparation and dosing of reagents. According to the technological schemes, the divisions servicing the main and auxiliary processes carry out: hydrotransportation of tail pulp; tailings (waste) storage; energy supply.

The technical devices and technological processes used in enrichment plants pose a potential danger. Therefore, failure to comply with industrial and environmental safety requirements during ore processing and enrichment can lead to various accidents and disasters causing harm to the life and health of workers and environmental pollution.

Thus, the main production departments use conveyor belts, which are fire hazardous along their entire length. Fires can occur at drive and tension stations or on the linear part of the conveyor. If a fire occurs at an enrichment plant, people may die, technological equipment may fail, and production may be stopped. Operation of lifting and transport equipment (overhead and gantry cranes, beam cranes, etc.) during loading and unloading operations is also associated with increased danger. When lifting and moving loads with cranes, it is possible for the load to fall from a height into the area where people are working, as well as for the crane to fall due to the destruction of its structures. Crane accidents are especially dangerous, as they cause great destruction of equipment, buildings and structures, are accompanied by accidents and cause great material damage.

All technological equipment at the enrichment plant is operated under voltage. Due to a short circuit, an overload of electrical circuits and an overvoltage of the electrical network may occur, followed by sparking and a fire. The supporting structures of the spans of technological galleries consist of trusses, roof and floor beams, and connections along the upper and lower chords of the trusses. The longitudinal stability of the gallery is ensured by a fixed spatial support, and the transverse stability by all supports. Violation of stability due to deflections of beams and trusses, corrosion, and failure of welded joints can lead to the destruction of galleries. Unsatisfactory condition of welded joints and foundations under the bunker and thickener, exceeding the nominal loading of the bunker lead to destruction and collapse. The presence of cracks, defects, traces of corrosion, a decrease in the strength of the metal walls of the mortar tank, unsatisfactory condition of the valves, leads to a violation of the tightness of the mortar tank with subsequent spillage of hazardous substances, poisoning of people and environmental pollution.

If the wear of the walls of the slurry pipeline is exceeded, malfunction and damage to shock-proof air columns and relief valves, the presence of corrosion of anchor supports, defects and cracks in welds and the heat-affected zone can lead to rupture of the pulp pipeline with subsequent pollution of the environment. If the condition of the dam is unsatisfactory, the crest of the reclaimed tailings of the dam and the alluvial dam exceeds the water level in the tailings pond and the crest of the primary dam and embankment dams at the upper slope exceed the beach, this can lead to the destruction of the dam and pollution of ground and surface waters, adjacent lands and atmospheric air. Thus, each production unit is characterized by types of accidents depending on the technological process and the production equipment used on it (Table 2).

Table 2. Types of accidents by production department

Production Division	Stages of the Technological Process	Types of Accidents
Main	Crushing is medium and fine	1. fire in the gallery of the conveyor belt 2. collapse of crane structures 3. fire of electrical equipment 4. destruction/collapse of the bunker 5. destruction of technological galleries
	The crushing is thin	1. fire in the gallery of the conveyor belt 2. fire of electrical equipment 3. collapse of crane structures
	Grinding	1. fire of electrical equipment 2. collapse of crane structures
	Flotation (main, control and cleaning)	1. fire of electrical equipment 2. collapse of crane structures
Auxiliary	Preparation of reagents	1. spill of a dangerous substance 2. collapse of crane structures
	Thickening	1. fire of electrical equipment 2. destruction/collapse of the thickener 3. collapse of crane structures
	Filtering	1. fire of electrical equipment 2. collapse of crane structures
Service	Hydraulic transportation of tail pulp	1. fire of electrical equipment 2. breakthrough of the pulp pipeline
	Tailings storage	1. destruction of the dam
	Electrical supply	1. fire in the transformer

Table 3. Technical criteria parameters for assessing the accident hazard indicator

Type of Accident	Technical Criteria Parameters
1. Spill of a dangerous substance	1. the condition of the consumable (solution) container; 2. the condition of the valve.
2.Destruction/collapse of the bunker	1. Loading the hopper; 2. condition of the base under the hopper; 3. the condition of the welded joints.
3.Destruction/collapse of the thickener	1. corrosion of load-bearing structures under the thickener; 2. the condition of the foundation under the thickener.
4.Collapse of crane structures	1. weight of the lifted load; 2. Condition of ropes or slings; 3. the condition of the crane components and parts.
5. Destruction of technological galleries	1. deflections of beams and trusses; 2. corrosion of load-bearing structures; 3. the condition of the welded joints of the supports; 4. condition of support assemblies and parts; 5. Dynamic loads during operation of the conveyor.
6. Destruction of the dam	1. the condition of the dam; 2. the minimum excess of the crest of the washed tailings of the dam and the alluvial dam above the water level in the pond of the tailings; 3. minimum excess of the crest of the primary dam and the collapse dams at the upper slope above the beach; 4. The length of the alluvial surface from the tails to the water edge of the primary dam.
7. Breakthrough of the pulp pipeline	1. the condition of the wall thickness of the pulp pipeline; 2. Condition of shockproof devices; 3. corrosion of anchor supports; 4. the condition of the welded joints of the anchor supports.
8. Fire at the conveyor belt gallery	1. the condition of the conveyor belt movement; 2. The temperature of the drive drum due to friction against the tape.
9. Electrical equipment fire	1. insulation of electrical wires and cables of equipment 2. current load of wires and cables of equipment 3. Condition of switching equipment, electrical equipment, wires and cables 4. Transient resistance.
10. Transformer fire	1. Transformer oil level; 2. Transformer load; 3. the condition of the magnetic circuit; 4. Transformer winding condition; 5. Condition of the power cable sheath; 6. The condition of the automatic control of the transformer operation.

According to the previous studies [43, 44], risk is a combination of two components – the probability of an event and its consequences. In this study, the accident danger indicator, reflecting the probability of a negative event occurring, was taken as the first component. The second component is an indicator of the severity of the accident, characterizing the severity of the consequences of environmental pollution when exposed to a damaging factor. Multifactor mathematical models have been developed to quantify risk components by applying the expert assessment method.

To determine the internal content of risk components, an analysis of legislative and regulatory technical documentation in the field of industrial and environmental safety regulating the activities of the enrichment plant was carried out [1, 2, 45, 46], information on accidents that occurred at similar production facilities was studied [3-11], and cause-and-effect relationships between accident risk factors were studied. The results of the study made it possible for each type of accident to determine the conditions under which they can occur and to formulate technical and environmental criteria parameters (technical and environmental criteria) and their values for assessing risk components. Table 3 presents the technical criteria for assessing the first risk component - the accident hazard indicator.

During the research, the types of environmental consequences resulting from an accident at an enrichment plant were determined. The response to the danger of all types of accidents presented in Table 1 is the severity of the consequences, which is reflected in the pollution of environmental components. Therefore, to assess the second component of risk, the following environmental criteria were adopted: State of land resources; state of atmospheric air; state of water resources.

5. ANALYSIS OF THE PROBABILITY OF AN ACCIDENT AND ITS CONSEQUENCES USING THE METHOD OF EXPERT ASSESSMENTS

As can be seen from Table 3, for each type of accident certain technical criteria parameters and three environmental parameters correspond. Moreover, each parameter has its own specific impact on the likelihood and consequences of an accident. Their hierarchy was determined on the basis of expert assessments.

Table 4, as an example, presents the results of a survey of experts on the degree of influence of factors on the risk of slurry pipeline rupture at an enrichment plant, as well as intermediate calculations to determine the Kendall concordance coefficient.

To determine the Kendall concordance coefficient, the arithmetic mean number of ranks is determined: $Q_{average}$ = (81+56+64+53)/4 = 63,5. Next, according to the data in Table 4 and formula (1), the value of the concordance coefficient is calculated:

Table 4. Expert assessments on the degree of influence of factors on the risk of slurry pipeline rupture

The Criterion Parameter	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	The Sum of the Ranks	Deviation from the Average	The Deviation Square
The condition of the thickness of the walls of the pulp pipeline	9	6	9	9	8	9	7	9	8	7	81	17.5	306.25
Condition of shockproof devices	4	4	8	6	5	6	6	6	7	4	56	-7.5	56.25
Corrosion of anchor supports	7	6	6	7	6	5	7	6	6	8	64	0.5	0.25
Condition of welded joints of anchor supports	6	4	5	7	5	5	5	7	5	4	53	-10.5	110.25
Sum											254		473

Table 5. Technical criteria parameters and their values for assessing the risk of slurry pipeline rupture

Technical Criteria Parameter			Values of the Technical Criterion Parameter	
Name	Final Score	Specific Gravity, *y*	Verbal Description	The Point Score, *b*
The condition of the thickness of the walls of the pulp pipeline *(b_1)*	8	0.32	according to the standard (draft)	0
			the wear of the walls of the pulp pipeline is up to 2.2 mm	60
			critical wear of the walls of the pulp pipeline (more than 2.2 mm)	100
Condition of shockproof devices *(b_2)*	6	0.24	fully functional condition of shockproof air columns and relief valves	0
			malfunction and damage of shockproof air columns and relief valves	100
The condition of the anchor supports *(b_3)*	6	0.24	corrosion damage up to 5 % of the cross-sectional area of the support	0
			corrosion damage up to 10 % of the cross-sectional area of the support	30
			corrosion damage up to 25 % of the cross-sectional area of the support	80
			corrosion damage of more than 25% of the cross-sectional area of the support	100
Condition of welded joints of anchor supports *(b_4)*	5	0.2	satisfactory condition	0
			there is a defect in the welds, there are non-melts, surges, uneven scaly surface of the welds	40
			there are cracks in the welds and the near-seam zone, partial destruction of the welds	80
			there is a rupture of welded joints	100

$$W = \frac{12 * 473}{100(64-4)} = 0.9$$

W=0.9 indicates a high degree of agreement among experts. The results of processing questionnaires and calculations of the Kendall coefficient for other types of accidents showed that the level of agreement between experts' opinions on assessing the degree of influence of criterion parameters on the probability of an accident occurring is high. The calculated values of W ranged from 0.7 to 0.9.

The integer arithmetic mean value µ was taken as the final score based on the obtained series of expert assessments. Based on the final scores, the specific gravity (*y*) of each criterion parameter was determined using formula (2):

$$y_i = \frac{g_i}{\sum_{i=1}^{n} g_i} \quad (2)$$

where, g_i is the final assessment of the significance of the i-th criterion parameter

Tables 5 and 6 present the results of the expert group's work on one type of accident – «slurry pipeline rupture».

From Table 5 it can be seen that the greatest influence on the probability of an accident has the "state of the thickness of the walls of the slurry pipeline" (specific gravity 0.32), the least - the "condition of the welded joints of the anchor supports" (specific gravity 0.2). From Table 6 it can be seen that the greatest influence on the accident severity indicator is exerted by the "state of land resources" (specific gravity 0.5), the least - by the "state of atmospheric air" (specific gravity 0.19). Similarly, an expert study was conducted on all types of accidents.

Each criterion parameter presented in Tables 5 and 6 can take on different qualitative and quantitative values. Not all values can be strictly measured, so they are mainly presented in the form of unformalized indicators and have a verbal description. Displaying qualitative values of criteria in symbolic form (in the form of numbers) was based on expert opinion. For technical criteria, experts, based on their own experience, assessed the values of the criterion parameter on a scale from 0 to 100, thereby reflecting the influence of each value on the probability of an accident within each parameter, that is, the significance of the value. The influence of the values of environmental criteria on the severity of the consequences of the realization of the danger of accidents at enrichment plants was assessed on a scale from 0 to 5, which made it possible to take into account both the absence of any changes in the components of the natural environment and those that were critical as a result of the accident.

Based on data on the degree of influence of a set of criterion parameters $\{n\}$ and the significance of their values on the possibility of the i-th accident occurring, the accident hazard indicator (OA_i) is determined using formula (3):

$$OA_i = \sum_{j=1}^{n} \gamma_j \times b_j \quad (3)$$

where, γ_j is the specific gravity of the j-th criterion parameter; b_j is score of the value of the j-th criterion parameter; n is number of criterion parameters by type of accident.

The calculated values of accident danger indicators according to formula (3) are assessed on the scale presented in Table 7, in which there are five intervals of values with their corresponding degrees of accident danger: insignificant, low, medium, high, extremely high. The calculated values of accident danger indicators according to formula (3) are assessed on the scale presented in Table 8, in which there are five intervals of values with their corresponding degrees of accident danger: Minor, low, medium, high, extremely high. The accident danger indicator varies from 0 to 100. When the indicator is zero, there is no risk of an accident, and when the indicator is 70 or more, the risk of an accident is extremely high.

To determine the second component of risk - accident severity (TA_i) - based on the data in Table 6, a comprehensive assessment of the impact of the damaging factor on environmental components as a result of an accident is determined using formula (4):

$$TA_i = \sum_{j=1}^{3} \nu_j \times d_j \quad (4)$$

where, ν_j is the specific gravity of the j-th criterion parameter; d_j is score of the value of the j-th criterion parameter.

Table 6. Environmental criteria parameters and their values for assessing the severity of the consequences of accidents at enrichment plants

Environmental Criteria Parameter			Environmental Values the Criterion Parameter	
Name	**Final Score**	**Specific Gravity, y**	**Verbal Description**	**The Point Score, *b***
The state of land resources (d_1)	8	0.50	No changes in land resources	0
			There are surface changes in land resources at a depth of 1 cm, in places there are minor changes in vegetation cover (up to 10%)	1
			There are changes in the content of the chemical composition of the soil at a depth of 1-5 cm, the death of the animal and plant world (up to 25%)	2
			There are changes in the content of the chemical composition of the soil at a depth of 5-10 cm, the death of vegetation (up to 60%) and wildlife (up to 50%)	3
			There are changes in the content of the chemical composition of the soil at a depth of 10-15 cm, almost complete degradation of flora and fauna (up to 90%)	4
			There are changes in the content of the chemical composition of the soil at a depth of more than 15 cm, the death of the animal and plant world	5
The state of the atmospheric air (d_2)	3	0.19	No pollution or compliance with maximum permissible concentrations (MPC) of pollutants	0
			Exceeding the MPC of pollutants from 1.1 to 2 times	1
			Exceeding the MPC of pollutants from 2.1 to 4	2
			Exceeding the MPC of pollutants from 4.1 to 6	3
			Exceeding the MPC of pollutants from 6.1 to 10 times	4
			Exceeding the MPC of pollutants by more than 10 times	5
State of water resources (d_3)	5	0.31	No environmental pollution or compliance with regulatory requirements	0
			Ingress of pollutants into water bodies, the excess of which according to the MPC is from 1.1 to 2 times	1
			Ingress of pollutants into water bodies, the excess of which according to the MPC is from 2.1 to 4 times	2
			Ingress of pollutants into water bodies, the excess of which according to the MPC is from 4.1 to 6 times	3
			Ingress of pollutants into water bodies, the excess of which according to the MPC is from 6.1 to 8 times	4
			Ingress of pollutants into water bodies, the excess of which according to the MPC is more than 8 times	5

Table 7. Scale for assessing the accident danger indicator

Accident Hazard Indicator Intervals	Degree Accident Danger	Description
$OA_i = 0$	Absent	An accident will not happen
$0 < OA_i \leq 19$	Minor	An accident is hardly possible
$20 \leq OA_i \leq 29$	Low	An accident is unlikely
$30 \leq OA_i \leq 49$	Medium	An accident is not typical, but it is possible
$50 \leq OA_i \leq 69$	High	It is very likely that an accident will occur
$70 \leq OA_i \leq 100$	Extremely high	An accident is likely to happen

Table 8. Scale for assessing the severity of an accident at an enrichment plant

Indicator Severity of the Accident	Degree Severity of the Accident	Description
$TA_i = 0$	Absent	No pollution of environmental components
$0 < TA_i \leq 1$	Minor	Contamination of environmental components that can be eliminated by the enterprise within up to 1 month.
$1 < TA_i \leq 2$	Medium	Contamination of environmental components that can be eliminated by the enterprise within up to 6 months.
$2 < TA_i \leq 3$	Significant	Pollution of environmental components, which can be eliminated within up to 18 months by the enterprise and/or, if necessary, attract borrowed funds
$3 < TA_i \leq 4$	High	Pollution of environmental components that can be eliminated within up to 2 years by the enterprise and/or, if necessary, attract borrowed funds
$4 < TA_i \leq 5$	Critical	Pollution of environmental components that can be eliminated within more than 2 years by the enterprise and/or, if necessary, attract borrowed funds

The specific gravity of environmental criteria presented in Table 6 are applicable for the first seven types of accidents presented in Table 3. Fires at enrichment plants have a greater impact on the atmospheric air. Therefore, during an expert study on the degree of influence of the environmental criterion on the severity of the accident, the following specific gravity were obtained: state of land resources – 0.4; state of atmospheric air – 0.5; state of water resources – 0.1.

These specific gravity values are recommended to be used in formula (4) to assess the severity of consequences in case of fires on the conveyor belt gallery, in electrical equipment and transformers. The calculated values of accident severity indicators according to formula (4) are assessed on the scale presented in Table 8. The accident severity indicator varies from 0 to 5 and has five intervals of values from minor severity to critical, which take into account the time period and the attraction of third-party funding to eliminate the consequences of accidents at enrichment plants.

6. RISK ASSESSMENT

To assess the risk of an accident, it is recommended to use the «Risk Assessment Matrix» presented in Table 9. The matrix allows, based on various combinations of indicators of the danger of an accident and the severity of consequences, to obtain a generalized risk assessment and rank the levels.

The matrix (Table 9) shows the threshold values of indicators of the danger of an accident and the severity of their consequences. At the intersection of rows and columns, one of five levels of accident risk is determined. Table 10 provides a description of the risk levels and recommended corrective actions.

Table 9. Risk assessment matrix

Accident Hazard Indicator	An Indicator of the Severity of the Consequences					
	$TA_i = 0$	$0 < TA_i \leq 1$	$1 < TA_i \leq 2$	$2 < TA_i \leq 3$	$3 < TA_i \leq 4$	$4 < TA_i \leq 5$
$OA_i = 0$	absent	absent	absent	absent	absent	absent
$0 < OA_i \leq 19$	absent	negligently small	small	moderate	elevated	elevated
$20 \leq OA_i \leq 29$	absent	small	moderate	elevated	elevated	critical
$30 \leq OA_i \leq 49$	absent	moderate	elevated	elevated	critical	critical
$50 \leq OA_i \leq 69$	absent	elevated	elevated	critical	critical	critical
$70 \leq OA_i \leq 100$	absent	elevated	critical	critical	critical	critical

Table 10. Description of accident risk levels

Name of Accident Risk Level	Description of Risk Level	Corrective Measures
Negligible small / «blue»	does not pose any threat to the enterprise, the environment and the population	no need to apply protective measures
Small / «green»	posing an insignificant threat to the enterprise and the environment that the organization can tolerate without violating legal obligations and policies in the field of industrial and environmental safety	no protective measures are required, high-quality production control and environmental monitoring are required
Moderate / «yellow»	posing a certain threat to the enterprise, the environment and public health	strengthening of production control and environmental monitoring is required, as well as the development and implementation of preventive measures to reduce the likelihood of accidents and the severity of their consequences.
Elevated / «orange»	posing a high threat to the enterprise, the environment, and public health	a temporary shutdown of production is required until the risk is reduced to a «green» level; urgent measures are needed to reduce the likelihood of an accident and prevent environmental pollution
Critical / «red»	posing an extremely high threat to the enterprise, the environment, public health and future generations.	immediate cessation of production activities is required until the risk is reduced to a «green» level

The purpose of accident risk assessment is to select effective and efficient measures to improve industrial and environmental safety. Eliminating all dangers at once is not always possible. The purpose of accident risk assessment is to select effective and efficient measures to improve industrial and environmental safety. This determination of the priority of activities will make it possible to solve first the primary issues in the field of industrial and environmental safety, and then concentrate on issues with less significant problems, thereby ensuring the continuity of the risk management process.

7. RESULTS AND DISCUSSION

Based on the results of the expert study, multifactorial mathematical models were obtained, the factor space of which depends on the number of criterion parameters for assessing the danger and severity of accidents. So, in the example given in Table 6, there are 4 technical criteria for determining the risk indicator for the destruction of a slurry pipeline at a enrichment plant. In accordance with formula (3), a multifactor mathematical model for assessing the hazard indicator for this type of accident will have the following form:

$$OA_i = 0.32 * b_1 + 0.24 * b_2 + 0.24 * b_3 + 0.2 * b_4$$

where, b_1 is a score for the condition of the wall thickness of the slurry pipeline; b_2 is score assessment of the state of shockproof devices; b_3 is score of the condition of anchor supports; b_4 is score assessment of the condition of welded connections of anchor supports.

For other types of accidents, multifactor models are compiled in the same way to calculate and evaluate the hazard indicator. Points for each technical criterion are taken based on the results of production control and inspection of process equipment. For example, as a result of an equipment inspection, we have the following data: wear of the slurry pipeline walls up to 2.2 mm; fully operational condition of shockproof air columns and relief valves; corrosion damage up to 10% of the cross-sectional area of anchor supports; there is a defect in the welds, there are lack of fusion, sagging, uneven scaly surface of the welds.

In accordance with Table 5 and formula (3), the risk indicator for slurry pipeline rupture is equal to:

$$OA = 0.32 * 60 + 0.24 * 0 + 0.24 * 30 + 0.2 * 40 = 34.4$$

According to the scale presented in Table 7, the degree of danger of an accident is medium, an accident is possible.

In accordance with formula (4) for the considered example “slurry pipeline rupture”, the multifactor mathematical model for assessing the accident severity indicator will have the following form:

$$TA = 0.5 \times d_1 + 0.19 \times d_2 + 0.31 \times d_3$$

Scores for the value of each environmental criterion are taken based on the results of environmental monitoring. For example, if a destruction of the pulp pipeline, the following consequences are possible: surface changes in land resources are observed at a depth of 1 cm, in some places minor changes in vegetation cover are observed (up to 10%); absence of air pollution; entry of pollutants into water bodies, exceeding the MPC from 1.1 to 2 times.

In accordance with Table 6 and formula (4), the accident severity indicator will be equal to:

$$TA = 0{,}5 \times 1 + 0{,}19 \times 0 + 0{,}31 \times 1 = 0{,}81.$$

According to the scale for assessing the severity of accidents (Table 9), when a slurry pipeline ruptures, the impact on environmental components is minor. Thus, the application of formulas 3 and 4 allows, based on initial data presented in the form of qualitative values, to obtain quantitative indicators of the danger and severity of accidents and subsequently a quantitative risk assessment. The generalized risk assessment for the type of accident under consideration has a moderate level, i.e. destruction of the pulp pipeline poses a certain threat to the enrichment plant and the environment and requires constant monitoring of risk factors.

8. CONCLUSIONS

The article presents an expert approach to assessing technogenic risk using the example of an enrichment plant using the flotation method. Accident risk assessment is based on technical and environmental criteria parameters obtained by summarizing the opinions of specialist experts about the possibilities (or probabilities) of accidents occurring and the severity of their consequences. The consistency of expert opinions was assessed using the Kendall concordance coefficient, which showed a high level of consistency in the work of experts. Parameters on the state of the technological equipment used at the enrichment plant were adopted as technical criteria. Environmental criteria take into account the state of environmental components after an accident. The use of an expert approach to accident risk assessment allows the use of both quantitative and qualitative criteria.

Based on the obtained criterion parameters, multifactorial mathematical models have been developed that make it possible to obtain a quantitative assessment of the indicators of the danger of accidents and the severity of the consequences. For calculations, the values of technical criteria are taken based on the results of production control and inspection of process equipment, and environmental criteria - based on the results of environmental control and monitoring.

To obtain a generalized assessment of the risk of accidents, a risk matrix has been developed, which provides 5 risk levels from "negligibly small" to "critical". A scale has also been developed with a description of corrective measures to eliminate the risk, which allows you to determine the order of measures. The "negligently low" level does not pose a threat to the environment and does not require preventive measures. The "critical" level poses an extremely high threat to the enterprise, the environment, public health and their future generation. At this level, it is necessary to stop production and take measures to reduce the risk to the "green" level. The generalized assessment of the risk of rupture of the pulp pipeline has a moderate level (yellow). This level of risk poses a threat to the enrichment plant, the environment and the public. To minimize the risk, enhanced production control, environmental monitoring and the implementation of preventive measures are necessary.

The presented expert approach to assessing the risk of accidents at enrichment plants has a unified character. This approach will further allow the development of criteria parameters and multifactorial mathematical models for various types of accident risk at production facilities in which there is insufficient or low-quality information about the object of risk. In the course of scientific research, this technique was used as part of contractual work, in the design of environmental impact assessment of the enrichment plant in Central Kazakhstan.

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