

Monitoring the safety of areas contaminated with radiation hazardous waste

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Abstract. The article analyzes the current situation in Ukraine with radiation hazardous waste storage facilities. The environmental and economic consequences of the problem associated with the accumulation, storage and disposal of waste are assessed. Based on the requirement for long-term preservation and compliance of radioactive waste storage facilities with current regulations and minimization of maintenance costs, a strategy for remediation of areas contaminated with radioactive waste and further management of such waste is proposed. The strategy consists of implementing a set of remediation measures on contaminated territories that allow them to be removed from maintenance and regulatory control and return these territories to free, unlimited or at least useful use by local communities or new owners. The organizational and economic mechanism for implementing the strategy for further management of radioactive waste storage facilities, which includes preparatory, selective, design, technological and monitoring stages, is considered. It is shown that monitoring of the state of territories contaminated with radiation hazardous waste is a prerequisite for both the transfer of these territories for use by new owners and their further use. The main requirement for the monitoring system is to ensure that the risk of hazardous events is reduced to an acceptable value under conditions of minimal costs for its creation and operation. A two-level structure of the monitoring system is proposed, including a basic system that provides control of radiation dose rate, transmission, storage of information, assessment of changes, risk determination, decision-making on the need for preventive measures, and an additional system that provides information necessary for continuous adjustment of the remediation process and monitoring of the state of the territories at the request of the basic system.

1. Introduction

Human activities generate a huge volume of diverse wastes that significantly impact the environment. These wastes pollute the air, water, and soil, causing extensive harm to ecosystems and biodiversity [1]. They also contribute to the accumulation of harmful substances in the environment, which can have long-term detrimental effects on human health and well-being [2]. The presence of unmanaged or improperly managed waste often necessitates the establishment of waste dumps, which not only occupy valuable land resources but also require ongoing maintenance [1, 3]. The need to mitigate the negative impacts of these wastes places a financial burden on both governments and private entities, diverting resources that could be used for other critical areas [3, 4]. Ultimately, this issue underscores



the urgent need for effective waste management systems and sustainable practices to protect the environment and ensure public safety [1, 5].

One of the methods of the safety of areas contaminated with radiation hazardous waste is thermochemical destruction [2, 6]. It involves the controlled application of heat and chemical processes to neutralize hazardous waste while ensuring the safety of contaminated areas [7]. Pyrolysis, one of the key methods, decomposes radioactive waste at high temperatures in the absence of oxygen, reducing waste volume and preventing the release of harmful emissions [8]. Gasification, another method, converts waste into a synthesis gas (syngas) at controlled temperatures, which can be further treated to remove radioactive particles [6, 9]. Plasma arc technology employs extremely high temperatures to break down waste at a molecular level, encapsulating radioactive residues in a stable vitrified form [10]. Advanced containment systems, including sealed reactors and negative pressure environments, are critical to prevent radioactive releases during these processes [10, 11]. The sophisticated filtration systems, such as HEPA filters and chemical scrubbers, are used to capture and neutralize any particulates or gases generated [10, 12]. The integration of these methods ensures the safe treatment and management of radioactive waste, minimizing environmental and human health risks [10, 11, 13].

In Ukraine, the extractive industry focused on the development of natural mineral deposits stands as the most significant source of waste generation [1, 5, 14]. This sector produces vast quantities of waste, much of which has long-term environmental and health implications. Among these wastes, uranium production waste occupies a particularly concerning position due to its hazardous and radioactive nature [15]. Historically, such waste was often managed without adequate environmental or economic justification, leading to its accumulation in areas that were poorly suited for long-term storage [14, 16]. Alarmingly, many of these waste sites were established in urbanized areas, where population density heightened the associated risks [17]. The proximity of these waste dumps to uranium ore enrichment and processing facilities further compounded the problem, creating zones of heightened contamination and potential exposure [18]. This situation underscores the urgent need for improved waste management strategies to address the legacy of hazardous waste in Ukraine's extractive industry [19].

The storage facilities of the Prydniprovsky Chemical Plant (PCP), which was engaged in industrial processing of uranium ores and other uranium-containing raw materials from 1948 to 1991, are in Kamianske and adjacent territories. Nine tailing ponds for uranium ore processing products were constructed on the territory, accumulating about 42 million tons of waste with a total activity of more than $31.8 \cdot 10^{14}$ Bq. At present, these radioactive waste storage facilities remain a source of threat to employees of enterprises and residents located in the territories adjacent to the storage facilities, which necessitates protection and supervision of the storage facilities, as well as periodic activities aimed at maintaining the safe condition of the storage facilities [1, 20]. All this leads to significant costs for the protection of the storage facilities, monitoring their condition and remediation, and given that the activity of the waste in the storage facilities has not actually decreased for thousands of years, the issue of further management of uranium production waste requires an urgent solution.

The world has accumulated considerable experience in successfully addressing the issues of uranium production waste management [21]. The study of these issues is devoted to the works of such scientists as V. Voitsekhovych, I. Mahony [22], N. Sanzharova, S. Fesenko [23], A. Bousher [24], K. Andersson [25] and others.

According to V. Wojciechowicz and I. Mahony, the main principle in deciding on further management of uranium production waste and making decisions on certain remediation measures is to expect more benefits from their implementation than harm [22]. At the same time, in accordance with the principle of optimization, the most optimal option should be chosen among all possible remediation options [23].

Earlier, when choosing a radiation protection strategy, several European countries tried to use approaches based on comparing the cost of remediation measures with the economic assessment of the risk value, which consisted in determining the damage from exposure of the population at a

conditional number of fatalities from exposure in the case of no measures [24]. Based on this, the appropriate level of cost of measures to reduce the unit of averted radiation dose was determined. The risk of long-term consequences was assumed to be 0.05 cases per Sievert, and the average life expectancy with cancer was assumed to be 15 years [25].

However, this approach did not work in most cases. It was impossible to justify the need for costly remediation measures based on radiological indicators alone. In most cases, the choice of remediation measures was determined by the social and political component rather than radiological feasibility [26]. Decisions were usually made regardless of the available indicators of radiation contamination but based on social protection considerations or from the standpoint of creating comfortable conditions for living in contaminated areas [27]. In other words, when choosing remediation measures, not only objective but also subjective factors are taken into account: social, legal requirements, and experience of similar measures in other countries.

To take into account various arguments when making a decision and choosing a particular strategy, the methodology of multifactorial analysis (MAA) was proposed [28]. This methodology allows taking into account both objective and subjective components: health factors, economic and social factors, etc. However, when using this methodology, the result was often ambiguous, and largely depended on who conducted the analysis and to what extent they were interested in certain results of the analysis [29].

It should be noted that each radiation hazardous waste storage facility is a unique facility. Storage facilities differ from each other by their size, amount of accumulated waste, radiation characteristics, presence and type of facilities in the adjacent territories, terrain, etc. In view of this, the available examples of successful resolution of the issue of further management of uranium production waste are not universal, and the problem of further management of uranium production waste and selection of remediation measures is quite urgent [30]. The current situation at radiation hazardous waste storage facilities is largely due to the lack of a clear, scientifically based strategy for their further management. Therefore, to successfully solve the problems related to the selection of certain areas of remediation of territories contaminated with radiation hazardous waste, it is first necessary to have a clearly defined strategy for further actions in this direction.

2. Methods

The methodology for monitoring the safety of areas contaminated with radiation-hazardous waste involves a systematic approach that integrates environmental assessment, risk analysis, and the use of advanced technologies [31]. The research begins with a comprehensive site survey to identify contamination levels, distribution patterns, and potential exposure pathways [32]. This is followed by the establishment of monitoring stations equipped with real-time dosimetry devices, ensuring continuous measurement of radiation levels. Data collection methods include soil sampling, air quality analysis, and water testing to detect radioactive isotopes and assess their movement within the environment [33]. The integration of geographic information systems (GIS) and remote sensing technologies enhances spatial analysis and facilitates the visualization of contamination zones, aiding in risk management and decision-making processes [31, 34].

The methods employed in the research prioritize precision and reliability, combining traditional fieldwork with modern laboratory techniques [35, 36]. Radiometric analysis using gamma spectrometry and alpha/beta counting quantifies the radioactive elements present in the samples. Advanced modeling tools, such as Monte Carlo simulations, are used to predict radiation dispersion and assess the effectiveness of containment strategies [37]. The study incorporates stakeholder engagement, involving local communities and regulatory bodies to align monitoring efforts with safety regulations and public health concerns [34]. This multi-disciplinary approach ensures a thorough understanding of contamination dynamics and supports the development of actionable safety protocols for affected areas [34, 38].

The method of economic analysis and economic-mathematical modeling was employed to evaluate both the financial losses caused by the contamination of territories with radiation-hazardous waste and

the costs associated with their remediation. These methods provide quantitative insights into the economic burden of environmental contamination, enabling a comprehensive assessment of direct and indirect impacts on affected regions [34, 39]. Additionally, the method of system analysis was applied, considering the full range of social, medical, biological, environmental, and economic factors to develop a holistic understanding of the problem [39, 40]. This approach ensures that no critical aspect of the issue is overlooked, allowing for a balanced and thorough evaluation. Complementing these, the method of scientific synthesis was utilized to integrate previously fragmented elements of the subject into a unified framework. This synthesis supports the formulation of effective strategies for managing uranium production waste and helps establish robust requirements for the structure and operation of monitoring systems.

3. Results and discussion

The world experience and available examples of the most successful solutions to the issues of further management of uranium production waste [21] show that success comes only when all groups of objective and subjective factors that influence the final decision are taken into account when choosing such a strategy. Among all these factors, the following groups of factors should be taken into account when choosing a strategy: social, biomedical, environmental and economic.

Social factors that should be taken into account when choosing a strategy include the following:

- anxiety about their future and the future of their descendants;
- distrust in the actions of both state and local authorities;
- violation of the comfort of living;
- attempts to follow the examples of others.

Medical and biological factors are primarily related to:

- possibility of accumulation of increased absorbed dose of ionizing radiation (compared to natural dose) by residents of the territories adjacent to the storage facilities
- increased absorbed dose of ionizing radiation for workers engaged in protection and supervision of the storage facilities;
- increased probability of long-term and genetic consequences in the population and workers as a result of increased radiation dose;
- increased probability of mutations among flora and fauna.

Environmental factors include the following:

- contamination of the earth's surface with radioactive substances in case of violations of the integrity of the protective cover;
- air pollution due to radon emissions and the ingress of fine dust particles with a high content of radioactive isotopes into the air;
- groundwater contamination due to filtration of soluble compounds with a high content of radioactive isotopes;
- the possibility of contamination of surface waters in the event of waste entering them in natural and man-made emergencies;
- withdrawal of large areas from beneficial use;
- existing restrictions on possible uses of the restored areas.

The most significant economic factors influencing the choice of strategy are related to the need to take into account:

- costs for measures to protect and monitor the condition of the storage facilities;
- costs for measures to bring the territory of the storage facilities to a safe condition;
- costs of measures to reduce the harmful impact of storage facilities on the population and the environment;
- costs for social activities;
- costs associated with the reburial of radioactive waste.

Despite the differences in storage facilities, there is a common task today, which is to minimize the costs and losses associated with the availability of all storage facilities, both now and in future periods

of time, while maintaining an acceptable level of safety for the public and personnel. In a formulaic form, this task is reduced to minimizing the functionality, which is the sum of current and future costs and losses under the constraints caused by the need to meet safety requirements

$$F = \sum C_a + \sum C_c^{br} + \sum L_a + \sum L_c^{br} \rightarrow \min, \quad (1)$$

where $\sum C_a, \sum C_c^{br}$ are accordingly, the amount of current and future expenses brought to the present time; $\sum L_a, \sum L_c^{br}$ are accordingly, the amount of current and future losses brought to the present time;

Restrictions due to the need to meet safety requirements [30] can be represented as a limitation as an additional to the natural annual equivalent dose to the public and personnel that is possible due to exposure to radiation hazardous waste storage facilities and is 1.0 and 20.0 millisieverts per year, respectively [30].

The analysis of the economic consequences of uranium production waste disposal at PChP performed in [41] showed that among the various groups of costs and losses caused by this disposal, the most significant are the costs of measures to protect and monitor the condition of radioactive waste storage facilities and measures aimed at bringing the facilities to a safe condition and reducing their harmful impact on the environment. Thus, for the period from 2009 to 2016, the actual cost of protection and supervision measures amounted to UAH 453 million (an average of UAH 62 million per year in 2016 prices), while the cost of remediation measures for all programs for the same period amounted to UAH 166 million. Subsequently, expenditures on protection and supervision remained almost at the same level, while expenditures on remediation activities decreased significantly and are now practically not funded. In such a situation, the expected potential losses of the state related to the need for protection and supervision of the storage facilities over the next 100 years will amount to about UAH 11 billion. When resuming remediation programs for territories contaminated with radiation hazardous waste, the components of losses are as follows $\sum L_a, \sum L_c^{br}$ can be respectively represented as current and future costs of the society associated with the need for protection and supervision of radioactive waste storage facilities, and the cost components $\sum C_a, \sum C_c^{br}$, respectively, as current and current zed future costs of remediation measures, i.e. measures aimed at bringing the storage facilities to a safe condition and reducing their harmful impact on the environment.

The experience of remediation activities in many countries shows that with the right remediation strategy, it was possible to reduce future expenses for maintenance and monitoring of storage facilities to almost zero and to minimize future expenses for remediation activities. The available modern technologies for engineering and geotechnical measures in radiation-contaminated areas allow to create safe conditions there for a very long time near areas with unlimited natural resources use. It is based on the requirement for a stable and long-term condition of storage facilities that legislation and regulations of several countries set requirements for protective barriers (soil cover of storage facilities, presence of impervious screens, protective dams, etc.) They should ensure reliable protection of the storage facilities for at least 200 years [26, 27].

In view of the above, the strategy for further management of uranium production waste should be limited to the implementation of a set of remediation measures in contaminated areas that allow them to be removed from maintenance and regulatory control and return these areas to free, unrestricted or at least useful use by local communities or new owners.

When radioactive waste is stored after remediation activities have been completed, certain risks from unrestricted use of such areas may remain in some cases. In such cases, restrictions on the use and management of such areas may be imposed. For example, storage facilities should be fenced with appropriate safety signs. Only those objects or activities may be placed on the surface of the tailings facilities that are permitted by the design and are safe in terms of maintaining the surface and protective dams of the facilities in a specified condition.

As a rule, earthworks that could lead to a violation of the integrity of the soil cover are prohibited on the territory of the storage facilities for a long time (hundreds of years), construction of residential

buildings and arrangement of drinking and agricultural wells are not allowed. Requirements are introduced for vegetation cover and drainage systems. Unauthorized access to some areas may be prohibited. In most cases, the responsibility for compliance with safety requirements in the use of such areas lies with either local governments or owners, who, under certain conditions, may use such areas and are responsible for the safety of environmental management.

The organizational and economic mechanism for implementing the strategy for further management of uranium production waste storage facilities is shown in Figure 1. It includes the following 5 stages: preparatory, selective, design, technological and monitoring.

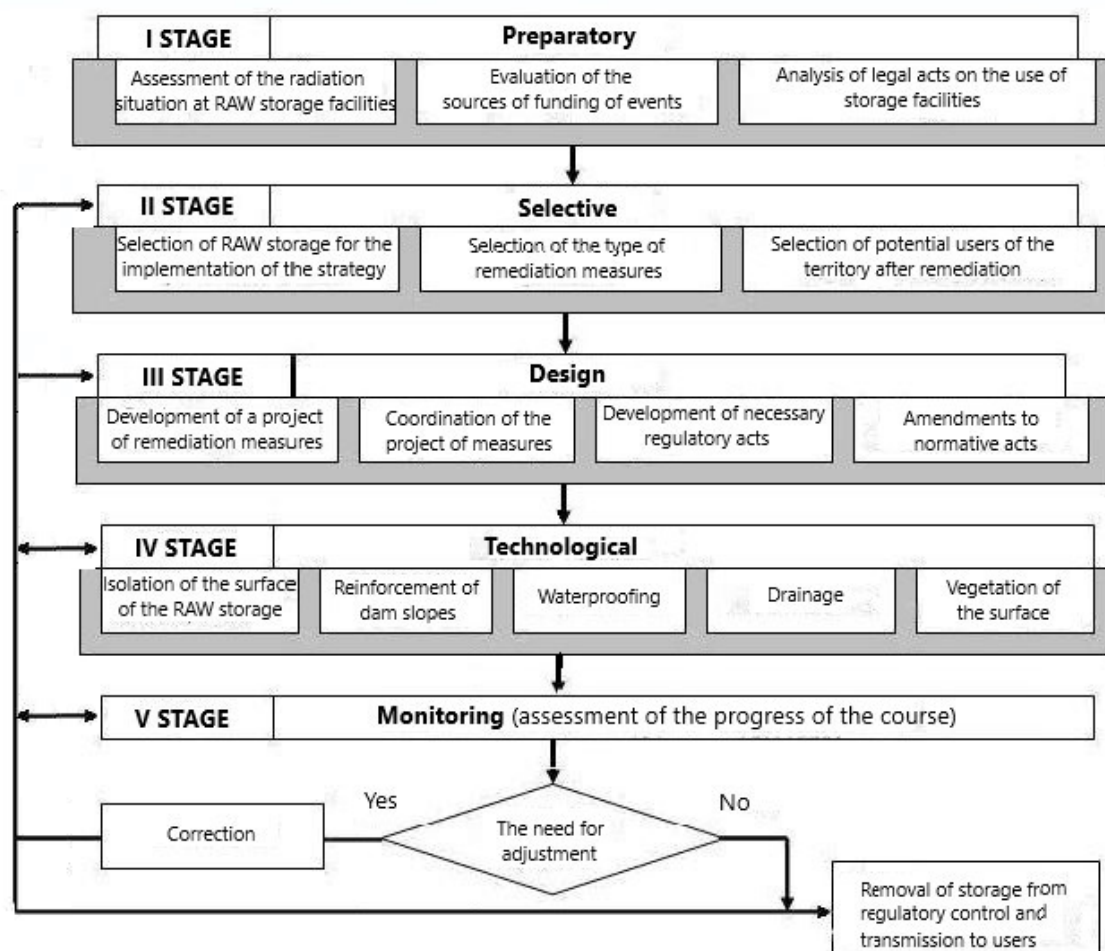


Figure 1. Organizational and economic mechanism for implementing the strategy for further management of storage facilities.

At the first stage, the radiation situation at the storage facilities is assessed (gamma radiation intensity, EDR, radon exhalation, condition of the cover, condition of protective dams, etc.), sources and possible amounts of funding for remediation are determined, and current legislation and regulations on the possible use of the storage facility territory after remediation measures are analyzed.

At the second stage, based on the data from the analysis of the condition of the storage facilities and the possible amount of funding for remediation activities, a specific storage facility (facilities) is selected to implement the selected strategy, and the areas of work are determined. A very important aspect for the selection of remediation measures is the decision to identify possible potential users of the storage facilities after remediation and to agree on the decision on further use of the territories and facilities. The most effective use of such facilities or territories is the beneficial use after bringing

them to an environmentally safe state. The position of stakeholders in implementing the strategy at this stage is crucial.

At the third, design stage, a remediation project is developed and approved, and, if necessary, regulatory legal acts or draft amendments to existing regulatory legal acts related to issues related to the withdrawal of territories from regulatory control and their transfer to new users are developed and approved. If necessary, issues related to granting permanent or temporary benefits to new users of the territories are agreed upon to increase their interest in using the storage facilities.

At the fourth stage, in accordance with the developed project, remediation activities are performed to remove the repository from regulatory control and transfer it to new users, which may generally include activities related to repository surface planning, soil cover improvement, strengthening of dam slopes, waterproofing, drainage, replacement or improvement of existing vegetation, etc.

An obligatory stage in the implementation of the chosen strategy is the administrative and public control over the project implementation to timely adjust it in accordance with the circumstances and conditions that may arise during the project implementation and the condition of the territory of the repositories transferred to the new owners (fifth, monitoring stage).

Monitoring, as a constant or regular observation of an object or process for the purpose of evaluation, comparison and forecasting, is used everywhere, in various fields, both in science and in management. Any managerial information processes include procedures for registering, collecting, transmitting, storing, processing, issuing information and making decisions based on the information collected [40].

Information technologies are the means and methods by which the procedures for registration, collection, transmission, storage, processing, issuance of information and decision-making based on the collected information in various information systems are implemented. With the development of information technology, almost all monitoring systems are now based on computers and information systems. In this case, monitoring systems are transformed into computer-based monitoring systems.

Monitoring can be divided into different types; the most common types of monitoring include the following:

- facility monitoring is designed to provide information necessary for continuous monitoring of the condition of radiation hazardous waste storage facilities, identifying and eliminating problems, and making decisions;
- process monitoring, designed to provide information necessary for ongoing planning and analysis of work, assessment of success or otherwise adjustment of remediation projects and programs, identification and resolution of problems and challenges, and use of opportunities as they arise;
- outcome or impact monitoring, aimed at assessing the changes caused by a remediation project or program.

At the heart of computer-based monitoring systems are monitoring programs that serve many purposes, depending on the type of monitoring and context. However, the main goal is to regularly collect information about the process and the object, and then use it to make continuous adjustments depending on the state of the system to maintain its effective performance.

The methodological basis of the safety monitoring system for territories contaminated with radiation hazardous waste should be the following provision: to ensure reduction of the risk of hazardous events to an acceptable value under conditions of minimal costs for the establishment and operation of the monitoring system.

In this case, the risk of hazardous events is defined as a combination of the probability of a hazardous event and the severity of its consequences. Reducing the risk of hazardous events to an acceptable value is achieved both by reducing the probability of a hazardous event occurring and by making decisions aimed at eliminating the factors that cause the significant severity of a hazardous event, as well as by promptly making management decisions aimed at reducing the severity of the consequences of a hazardous event. A generalized model of disaster risk management is shown in Figure 2.

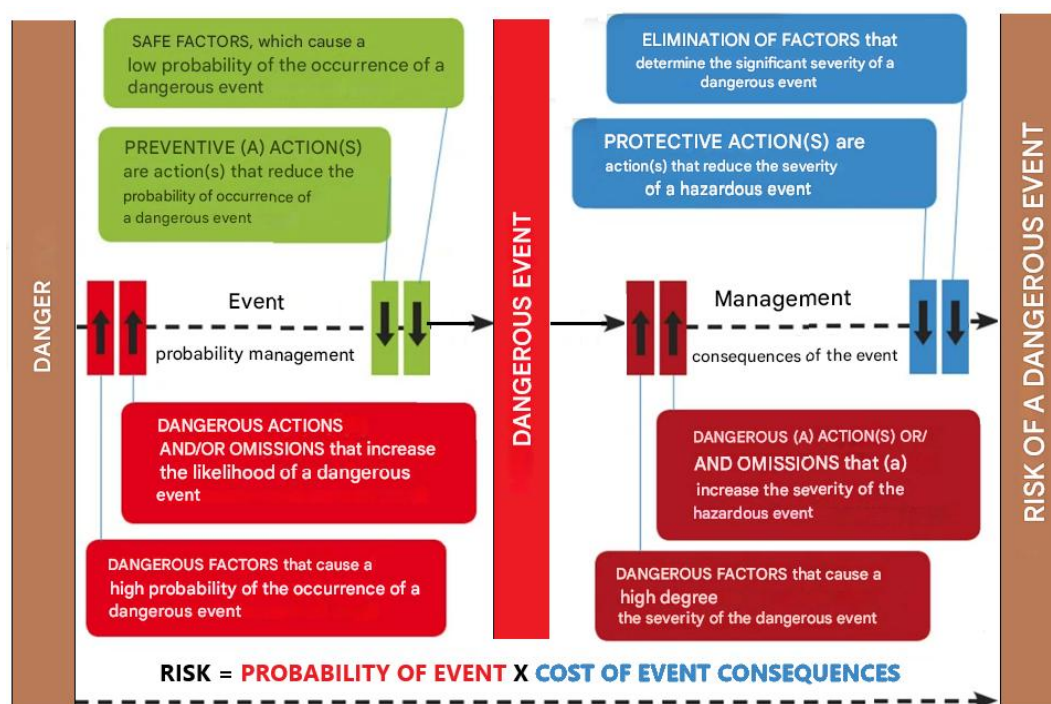


Figure 2. Hazardous event risk management model.

Based on the above model of hazardous event risk management, a two-level monitoring system is proposed, the structure of which is shown in Figure 3, which includes a basic system whose main purpose is to prevent the occurrence of hazardous events (event probability management) and an additional system whose task is to reduce the severity of the consequences of hazardous events.

The basic system is a permanent computer monitoring system that provides real-time monitoring of radiation dose rate, transmission and storage of information, assessment of changes, risk determination, and decision-making on the need for preventive measures. The main elements of the system are autonomous radiation dose rate sensors located directly on the territory of the storage facilities and the central information and analytical center located in the local unit of the State Emergency Service (SES). The number of sensors is selected depending on the area of the territory, but not less than five, one of which is in the central part of the storage facility and four at equal distances around the perimeter of the storage facility. This makes it possible to detect the fact of a dangerous increase in radiation dose rate and to geographically assess the possible location of dangerous violations of the protective soil layer.

An autonomous dosimeter of the GammaTRACE type [42], which has passed state acceptance tests in Ukraine and is included in the State Register of Measuring Instruments, can be used as a sensor for the basic monitoring system. The energy-saving electronic technology ensures continuous use of the GammaTRACER sensor for ten years without any maintenance. In addition to the internal power supply, the detector can be powered from an external power supply or from a solar panel. The electronic circuitry of the detector and the power supply (lithium batteries) are housed in a sealed, weatherproof housing. The sensors can be equipped with an RS-485/232 interface for data transmission via cable or a VHF module for wireless data transmission. This makes it possible to combine them into a single information network. An example of such a combination is the SkyLINK/ShortLINK system [43], the main component of which is the GammaTRACER sensor.

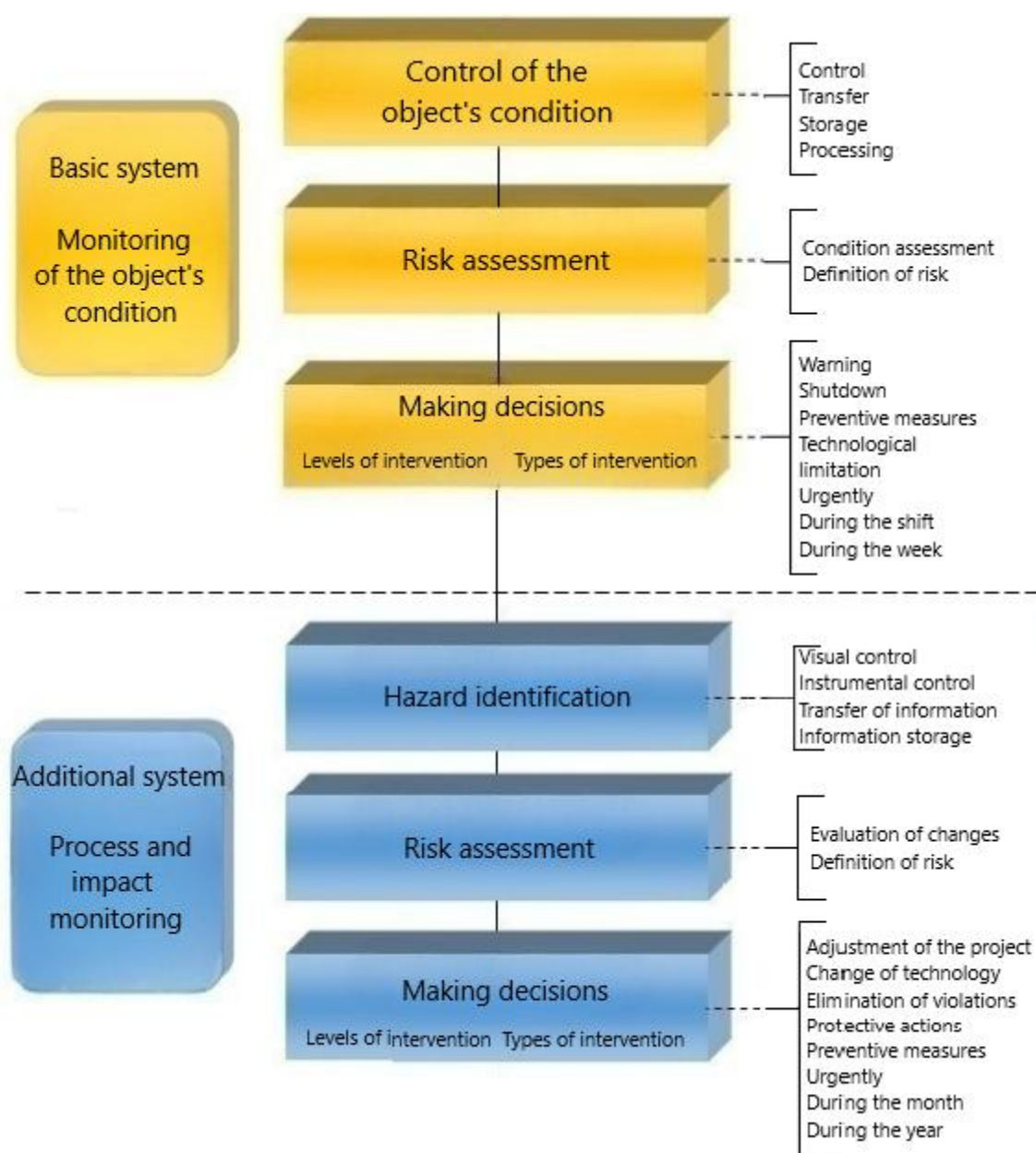


Figure 3. Structure of the system for monitoring the safety of territories contaminated with radiation hazardous waste

The SkyLINK/ShortLINK system is able to comprehensively solve the following tasks: current control of the radiation situation in the specified territory; timely detection of trends to change the radiation state of the territory; work in the event of disturbances in the power supply, communications and communication systems, to ensure the receipt of information related to meteorological parameters and other factors, to forecast the risk of the development of an emergency situation and assess the potential radiation impact on personnel, the population and the environment: timely and complete transmission of information in the monitoring system from the primary systems of objects to higher-level radiation monitoring systems both from an independent radio channel at a distance of up to 5 km (short-range communication system) or up to 100 km (long-range communication system), as well as through other communication channels communication (modem, Internet, cable network, etc.).

When SkyLINK/ShortLINK is used as the main element of the basic monitoring system, it should be linked to each specific storage facility, which means taking into account the areas of its use (creation of park areas, construction of parking lots, open warehouses; sports grounds, creation of parking lots for technical equipment; location of power plants, garden centers, etc.), territorial location of the storage facility, presence of economic facilities, residential areas, etc. on the territory of the storage facility and adjacent to it. In addition, it is necessary to develop software for risk assessment and provide recommendations to site owners, SES and territorial authorities on the types and levels of intervention in case of detection of elevated actual radiation dose rates or dangerous trends in their change over time in the territory of the storage facilities.

The purpose of the additional system is to conduct monitoring of the state of the territories at the request of the basic system and provide information necessary for both continuous adjustment of the remediation process and elimination of hazards identified during monitoring of the state of the territories. Territory monitoring in case of detection of a higher level of radiation dose and determination of its causes (unauthorized earthworks, erosion of the protective shielding layer of soil, etc. In addition, if necessary, the local unit of the State Emergency Service may be involved in monitoring the condition of the territories, including by inspecting the territories using unmanned aerial vehicles or directly visiting the storage facility to inspect its condition.

All information on hazardous incidents, their causes, consequences, measures taken to eliminate them, costs of their implementation, etc. is accumulated in the central information and analytical center of the SES territorial unit and used for feasibility studies of decisions aimed at eliminating hazards and adjusting the remediation process, including taking into account the opportunities offered using artificial intelligence.

4. Conclusions

The strategy for further management of uranium production waste at PChP should be limited to implementing a set of remediation measures in contaminated areas that would allow them to be removed from maintenance and regulatory control and return these areas to free, unrestricted, or at least beneficial use by local communities or new owners. The condition for implementing such a strategy is to maintain compliance of the storage facilities with the current regulatory legal acts on radiation safety and minimize the costs of storage facility maintenance. At the same time, the organizational and economic mechanism for implementing the strategy for further management of uranium waste storage facilities at PChP should include preparatory, selective, design, technological, and monitoring stages. Taking into account that the risk of hazardous events is defined as a combination of the probability of an event and the severity of its consequences, a generalized model of hazardous event risk management is proposed.

It is shown that monitoring the state of the territories contaminated with radiation hazardous waste is a prerequisite both for their transfer to new owners and for their further use. A two-level structure of the monitoring system is proposed, including a basic system that provides control of radiation dose rate, transmission, storage of information, assessment of changes, risk determination, decision-making on the need for preventive measures, and an additional system that provides information necessary for continuous adjustment of the remediation process and monitoring of the state of the territories at the request of the basic system.

In the future, the system for monitoring the safety of territories contaminated with radiation hazardous waste should be integrated into the general regional environmental monitoring system as a system for observing, collecting, processing, transmitting, storing and analyzing information on the state of the environment, predicting their changes and developing scientifically based recommendations for making management decisions taking into account the socio-economic consequences of the impact of emergencies on the state of the territory and population.

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