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APPLICATION OF CAUSE-AND-EFFECT RELATIONSHIPS ON SUPPORT STRATEGIC DECISION-MAKING IN RADIOACTIVE WASTE MANAGEMENT IN UKRAINE

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Background: The accumulation and storage of large-scale radioactive waste (RAW) in Ukraine poses a serious threat to the environment. Approximately 2500 tons of nuclear fuel waste was generated during the operation of the RVPK-1000 reactors. About 2800 tons of RW are materials containing nuclear fuel, including reactor graphite, fuel dust, etc. **Objectives:** The study is aimed at finding the most rational processes for managing accumulated and newly generated radioactive waste. **Methods:** To resolve complex, poorly formalized problems, system analysis provides the best efficiency. In the current study, an attempt was made to apply exactly this method to the management of radioactive waste. **Results:** The problem of RW management is complex and requires consideration of numerous factors. The initial basis, should be a functional approach. That is, the representation of the entire system through functional subsystems – groups of objects on which they behave with RW, and the subsequent division of each of the functional subsystems into further subsystems according to the types of accumulated and generated RW (aggregate state, activity level, radionuclide composition, etc.), which in turn is divided into elements. **Conclusions:** Proposed conceptual model structures the RW management system with all the variety of objects – sources of RW generation, types of RW and types of activities with them in separate subsystems – stages of RW management from their generation to disposal, and thus allows to significantly reduce the number of directions necessary for safety regulations in adoption of solutions.

Keywords: radiation safety; waste management; accumulation; system analysis.

INTRODUCTION

The environmental situation in countries with weak economies is quite complicated. This is clearly seen in the case of Ukraine and this situation refers to the problem of air pollution, water pollution, soil pollution and waste management (Khan et al., 2021; Freitas et al., 2023; Ayoub et al., 2024). Any military conflict can significantly worsen the ecological state of the environment, which in the future requires serious efforts to create suitable and safe conditions for people, flora and fauna. The presence of large-scale radioactive waste (RAW) stored on the territory of the country represents one of the most serious environmental problems due to its high level of danger.

To understand the relevance and importance of studying the process of radioactive waste (RW) management in Ukraine, it is necessary to know the quantitative indicators. Modern radioactive waste are radioactive and nuclear substances, and are sources of ionizing radiation. The sources of generation and accumulation of radioactive waste on the Ukrainian territory are nuclear power plants, state storage facilities (mainly the territories of specialized factories or the military-industrial complex), and territories for decontamination of radioactive waste. In addition to this, organizations generating radioactive waste include medical institutions, industrial enterprises and research laboratories. The largest generator of radioactive waste in Ukraine are operating nuclear power plants, which generate about 27 m^3 of solid radioactive waste and 35 m^3 of liquid radioactive waste per 1 billion kWh of electricity, depending on the type of reactor (DP, 2015).

The NPP has built and operate mode standard storage facilities for long-term storage of low, medium and high-levels of solid RW, storage facilities for long-term storage of liquid RW, installations for sorting, incineration, pressing, deep evaporation of solid RW and decontamination of equipment. Spent nuclear fuel from the VVER-440 and VVER-1000 reactors at Ukrainian NPPs, after being stored in the spent fuel pools available at each NPP power unit, must be transported to the Chernobyl zone to the Centralized Spent Nuclear Fuel Storage Facility (SNFSF). The Zaporozhye NPP should be singled out as an exception. This is explained by the fact that this nuclear power plant has a special storage facility at its production site for "dry" container storage of VVER-1000 nuclear fuel waste (Kondratiev et al., 2016). If the design life of the existing VVER-440 and VVER-1000 reactors is extended by 20 years, these reactors could produce approximately 17.5 thousand tons of spent nuclear fuel.

After the decommissioning of the Chernobyl NPP, during the current preparatory stage facilities were built and put into operation for the RW management, which was accumulated at the Chernobyl NPP and formed after its shutdown (Zaitov, 2002; Batiy, 2009; Hryhorash et al., 2017).

Considering the above the study is aimed at finding the most rational processes for managing accumulated and newly generated radioactive waste.

MATERIALS AND METHODS

Information on the volume and characteristics of radioactive waste was collected by the Institute of Public Administration and Research in Civil Protection (Kyiv, Ukraine).

Approximately 2500 tons of nuclear fuel waste was generated during the operation of the RVPK-1000 reactors. The main place of RW concentration in the Exclusion Zone is the Shelter Object. The Shelter Object facility and its industrial site contain from $4.0 \cdot 10^5$ to $174 \cdot 10^4$ m^3 of radioactive waste. As of the beginning of 2015, their total activity is approximately $4.1 \cdot 10^{17}$ Bq (listed based on the data from (Project INSC, 2016). About 2800 tons of RW are materials containing nuclear fuel, including reactor graphite, fuel dust, etc. In Shelter Object there is a constant accumulation of water of atmospheric, soil, condensation and technological origin. As a result of the interaction of water with radioactive materials, liquid radioactive waste is formed. Up to 900 m^3 of liquid RW is pumped out of the Shelter Object premises annually, to which there is access and which is transported to the liquid RW processing and storage system at the Chernobyl NPP (Shestopalova, 2008). During the operation of the Shelter Object, including the implementation of measures to turn the Shelter Object into an environmentally safe system (the stage of stabilization of the Shelter Object), significant volumes of solid radioactive waste are generated, which are currently buried in the Buryakovka radioactive waste disposal site. If we do not take into account the Shelter Object, then as of 2016 the total volume of radioactive waste in the Exclusion Zone is approximately 2.8 million m^3. Of the indicated amount, more than 2.0 million m^3 of radioactive waste are concentrated at the disposal point and temporary detention point with a total activity of about $7.4 \cdot 10^{15}$ Bq (Project INSC, 2017). On the surface layer of soil, in bottom sediments of water bodies, in vegetation and in other natural objects of the Exclusion Zone, the total activity of radioactive substances exceeds $8.5 \cdot 10^{15}$ Bq (Project INSC, 2017). The cumulative volume of radioactively contaminated materials located in the Exclusion Zone is estimated at 11 million m^3 (Project INSC, 2016). The main volume of these wastes refers to short-lived low and medium level RW.

On the sites of the special facilities of UkrGO "Radon" there are trench-type storage facilities for solid RW, well-type storage facilities for sources of ionizing radiation and storage tanks for liquid RW.

Ukraine has a uranium mining and processing industry, which has accumulated about 65 million tons of solid low-level waste.

According to the Ministry of Health of Ukraine (Azarov et al., 2012), there are about five thousand enterprises, institutions and organizations in the country that use different sources of ionizing radiation. 10,280 x-ray diagnostics, 254 x-ray therapeutic and 118 gamma-therapeutic devices, and 6 medical isotope devices are operated in the medical institutions.

The total annual average radioactive materials activity and sources for industrial and medical purposes can be about 1016 Bq, which does not exclude the occurrence of accidents associated with radioactive contamination of the environment and the personnel and population exposure (Figure 1, Table 1).

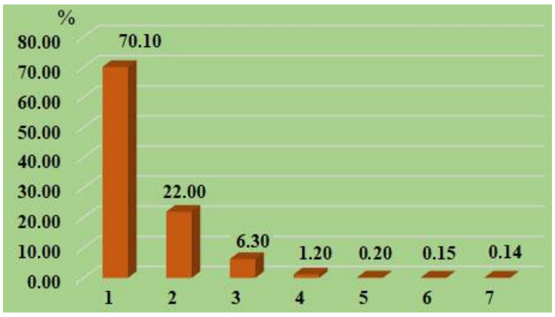

Figure 1. The percentage ratio for the distribution of radioactive waste: 1 – exclusion zone; 2 – shelter object; 3 – decontamination waste disposal sites; 4 – nuclear power station; 5 – repositories of special combines of UkrGO "Radon"; 6 – 1–3 units Chernobyl; 7 – research nuclear reactor (Kyiv)

Table 1. Total volumes of solid RW accumulated in Ukraine

Source	Nuclear power station	1–3 units Chernobyl	Shelter object	Exclusion zone	Decontamination waste disposal sites	Repositories of special combines of UkrGO "Radon"	Research nuclear reactor (Kyiv)
Volume, thousand m^3	33.2	2.5	600	1910	171	5.0	3.0

As can be seen, the amount of radioactive waste that requires disposal is from 3.5 to 5.0 million m^3. At the same time, the main contribution (from 2.9 to 4.2 million m^3) to these volumes is made by the Exclusion Zone and the Shelter Object (their share is 92%). Most of the waste (up to 97 – 98%) can be buried in surface storage facilities and only approximately 75,000 m^3 of RW are long-lived, and therefore should be buried in a geological repository.

The current study attempts to use systems analysis for radioactive waste management in Ukraine, due to the fact that systems analysis is recognized as an effective tool for solving complex, poorly formalized problems.

RESULTS AND DISCUSSIONS

Fundamentals and procedures for RW management are regulated by national legislation and international agreements. Radioactive waste, once generated, undergoes a series of transformation and movement processes before long-term storage or final disposal. Technologically, these are sequential processes: collecting and sorting of radioactive waste by category; processing and volume reduction; air conditioning; transportation; storage or burial.

As can be seen from the listed processes, the problem of RW management is complex and requires consideration of numerous factors. In this case, the most appropriate way is to use a systematic approach to solve this problem. Using the classical approach, by "system" we mean a set of parts that are in relationships and connections between themselves and form a kind of integral unity (Sharapov, 1983). Thus, all facilities in Ukraine that generate (accumulated) RW and handle RW can be represented as a RW management system.

Understanding all the variety of sources of RW generation, types of accumulated and generated RW, as well as various technological processes with RW, it is advisable to represent the system in the form of subsystems and its elements.

The initial basis, in our opinion, should be a functional approach. That is, the representation of the entire system through functional subsystems – groups of objects on which they behave with RW, and the subsequent division of each of the functional subsystems into further subsystems according to the types of accumulated and generated RW (aggregate state, activity level, radionuclide composition, etc.), which, in turn, are divided into elements. The main rationale behind the purpose of this work was the division of the entire RW management system into functional subsystems – groups of facilities where RW management is carried out. The subsequent division of each of the functional subsystems into further subsystems occurs according to the types of accumulated and formed RW (aggregate state, activity level, radionuclide composition, etc.), which, in turn, are divided into elements.

For the lowest link (element of the system), a specific type of activity (method of handling) for a certain type of RW, requiring regulation, was adopted. From the point of view of the system of normative regulation of safety in RW management, such an element is the regulatory influence on each specific type of activity with RW. Using the Thomas L. Saaty hierarchy analysis method, we represent the waste management system as a sequentially linear tree-like hierarchical structure (Figure 2).

To solve such complex problems of safety in the RW management, there is a universal methodology based on a systematic approach and system analysis. The versatility of this systematic approach allows us to consider security as a system and take actions towards improvement based on this understanding. Of course, the process of achieving the desired level of security is a challenging task for the future, which is not satisfactorily solved at the moment.

Shown in Figure 2 the hierarchical structure takes into account the main aspects of RW management. As a result of the analysis of 13 functional subsystems, it was determined that to regulate the safety of the entire system of radioactive waste management in Ukraine, more than 20 directions for making decisions on types of radioactive waste and more than 45 directions for making decisions on how to handle them are required. Such a process of RW management would be fragmented, unmanageable and practically unregulated. Using systematic analysis in our study, we moved from a verbal description of the problem to a formal one – the creation of a conceptual model of a system for the safe RW management. The model is shown schematically in Figure 3 and represents interrelated technological processes that take into account the RW aggregate state and its activities.

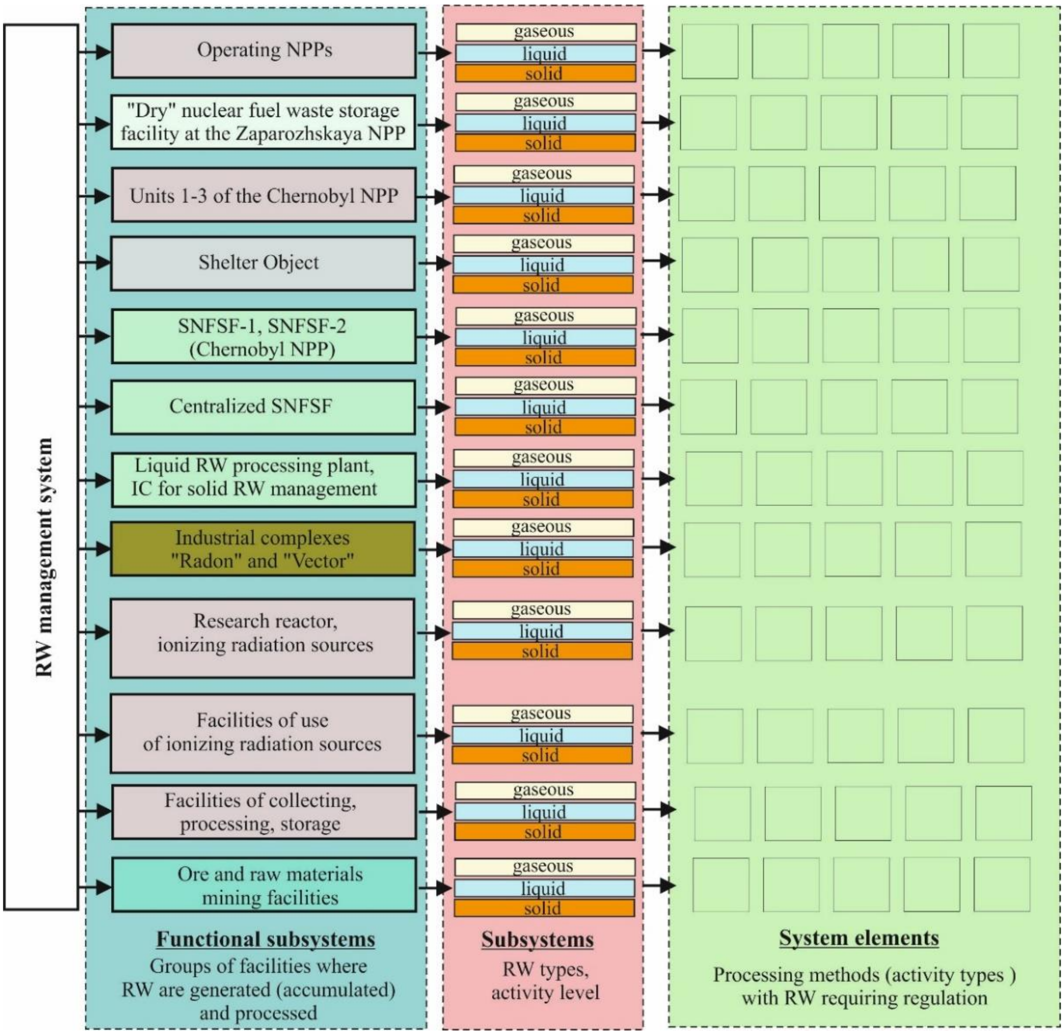

Figure 2. Hierarchical structure of the RW management system

The conceptual model structures the RW management system with all the variety of objects – sources of RW generation, types of RW and types of activities associated with them into separate subsystems – stages of RW management from their generation to disposal, and thus allows to significantly reduce the number of directions necessary for safety regulation in adoption of solutions.

In a general approach, three main stages are distinguished: preparatory, technological and final. This gradation is caused by the peculiarity of RW management processes. Each stage can be considered as a block of interconnected subsystems. The possibility of further structuring within the boundaries of individual stages also attracts attention. For example, for all types of RW aggregative states, a sub-stage of processing can be distinguished with subsequent separation of the elements of this segment.

Such a variant of representing the safe RW management in the form of a multilevel decomposition makes it possible to more adequately trace the links between the elements of the system and the logic of their interaction.

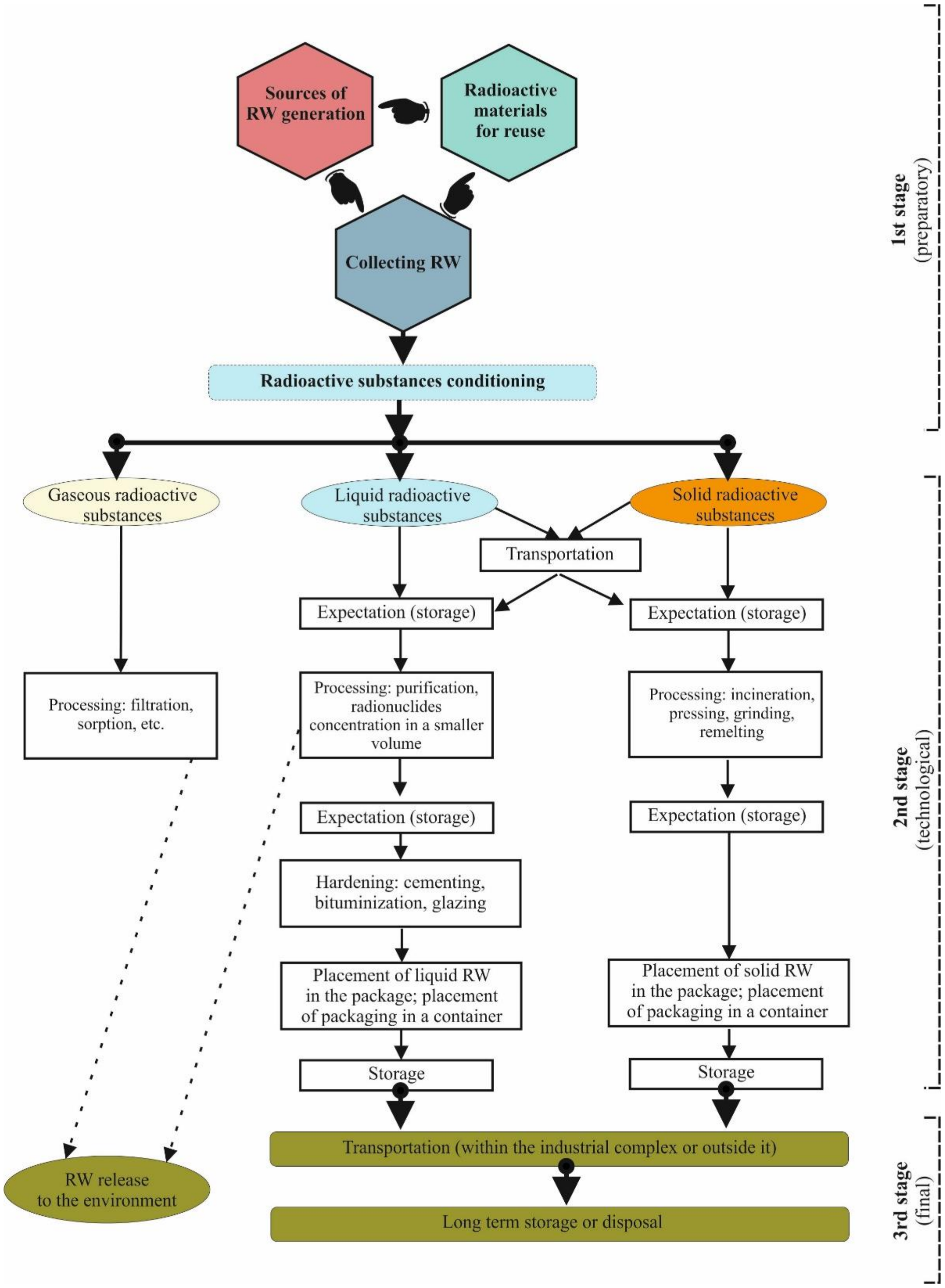

Figure 3. Conceptual model of a system for the safe RW management

CONCLUSION

If experts clearly understand the security logic, then this has a positive impact on the choice of the best technology for a further detailed strategy. At each appropriate level of detail, this approach should be applied to each of the waste management options being investigated. This should strive to establish clear links between the characteristics and volumes of radioactive waste, the technologies offered and the risks associated with them, safety and cost management mechanisms.

In this regard, the proposed hierarchical structure, as well as the conceptual model of the RW safe handling system, helps to shape further actions and accordingly develop technological processes based on the logic of which the main criterions are environmental safety and minimal risks for the population.

Author's statements

Contributions

All authors contributed to the study's conception and design, namely: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing: S.Y., V.S., I.M., and Ir.M.

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AI Disclosure

The author declares that generative AI was not used to assist in writing this manuscript.

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