METHODS OF RADIOACTIVE WASTE MANAGEMENT COSTS ESTIMATION UNDER INITIAL DATA UNCERTAINTY

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When plans are developed regarding further management of RW generated by nuclear sector, it appears quite hard to forecast the cost associated with the removal of the accumulated waste categorized as removable RW according to the Federal law № 190 On Radioactive Waste Management which is currently seen as a big challenge. Primary this is due to the limited initial data on the radioactive waste placed into storage facilities a long time ago. In this regard, this study aims to develop and test methods that can be used to assess the cost of radioactive waste management given the initial data uncertainty. Therefore, it presents a generalized financial and economic model providing cost assessment at various stages of RW management and identifies the parameters having the greatest impact on it. It also describes an approach that can be used to evaluate the uncertainties and to calculate the interval estimated radioactive waste management costs with given probabilities based on the Monte Carlo method. The discussed methods have been tested based on a case study that involved cost assessment for waste removal from the site of the Federal State Unitary Enterprise RADON (Sergiev Posad) and its subsequent disposal.

Keywords: *radioactive waste, waste management, removal, disposal, cost, expenses, uncertainty, statistical analysis, Monte Carlo method.*

Introduction and relevance

The challenge associated with most accurate preliminary assessment of radioactive waste (RW) management costs is seen as extremely relevant for nuclear operators and the international scientific communities. The IAEA and the Nuclear Energy Agency (NEA OECD) have come a long way to address it [1—4]. In Russia, an average of some 5—6 thousand m^3 of RW was conditioned per year with some 2.5 billion rubles spent from the federal budget under the FTP NRS-2 in 2016—2020. To calculate the costs to be covered under a state contract providing for such operations, on the one hand, a market profitability level should be provided for the contracting organizations, on the other hand, the efficiency of federal and special reserve fund spending should be maximized. Mistakes made at the planning stage may violate these principles and lead to inefficient performance by one of the parties involved: for the customer — in the event of an extremely overestimated cost, for the contractor - in the event of an underestimated cost ultimately resulting in a cost excess over the revenue.

Mistakes in the preliminary cost estimates mainly result from the initial data inaccuracies and the uncertainties of various parameters required for the calculations. This article describes a general approach addressing the problem of RW management cost assessment, including the costs associated with waste conditioning in accordance with waste acceptance criteria for disposal, its temporary storage, transportation and disposal under conditions of information uncertainty using probabilistic-statistical methods.

The developed methodological tools were tested on the example of cost estimates for RW removal from the main storage site operated by FSUE RADON.

Financial and economic model for RW management cost estimations

To begin with, it seems expedient to describe the general procedure followed to estimate the cost of RW removal from a storage facility (SF) at the preliminary planning stage, to build a financial and economic model and to identify the parameters affecting this assessment. Due to competitive procedures, the final cost of the contract is governed by the minimum cost proposed among the organizations engaged in this process, which, in turn, is determined by the cost method. Therefore, it is advisable to consider this problem in the context of cost assessment as regards work execution by potential contractors. Figure 1 shows the general flowchart for this procedure.

Zero stage (preparatory): collection and systematization of initial data on storage facilities and RW placed into these facilities, additional studies to elaborate the data, development of documentation. Costs are usually calculated by the resource method: the labor costs for personnel preparing data and necessary documentation, overhead costs, as well as costs for services delivered to provide additional studies (if necessary), sampling, etc. At the planning stage, costs (or some of the items) can be also calculated indirectly, for example as a share of the total cost or the cost for a group of operations.

Stage 1 involves RW removal, radiation monitoring and characterization of the waste. The costs for each operation are broadly defined as the product of the removed RW amount and the specific cost of the selected method (per 1 m^3 of waste). Costs for the performance of various operations are set individually by all potential contractors and are usually calculated based on the resource method (taking into account labor costs, depreciation of machines, material costs, etc.).

Before proceeding with stage 2, one should take into account that the physical volume of the waste after its removal may increase (loosening), therefore, the coefficient of volume change after this operation should be calculated. Depending on the waste parameters (category, type, state, whether the waste has been previously subjected to some processing), a schematic/simplified processing flowchart is developed, which can be represented as an oriented graph with RW conditioning sequences. It should be noted that at this stage, changes in the waste volumes after each operation considering various waste types generated, including secondary waste, should be forecasted which is seen as an essential part of this stage. Taking into account existing technical and engineering aspects and in accordance with the established methods, coefficients showing the changes in the total RW volume are set for all operations (for example, after pressing or fragmentation of metal waste, the total volume can be reduced by 1.5 times) and the waste generated due to an operation is segregated by type (e. g., after liquid decontamination or waste incineration). These parameters are identified either experimentally or based on the technical characteristics of the equipment applied. For RW held in a specific storage facility, it is necessary to specify the facilities that will be used during its further processing, and, if necessary, take into account the transportation costs, as well as the cost (depreciation) of the containers applied and the costs of their decontamination.

At stage 3 after waste segregation and before its pre-disposal conditioning, waste categories are set based on waste characterization (after its processing) according to certain criteria [5]. At this stage, for planning purposes, it is necessary to predict the distribution of waste by classes in accordance with the disposal requirements. It should be noted that this categorization is largely influenced by the radionuclide composition, which may vary quite widely. Therefore, the spread of values for different packages should be calculated. Practice shows that the specific activities of RW removed from a single storage facility can differ by orders of magnitude, as well as the proportion of radionuclides governing the RW class. In this case, often at the planning stage, data is available only on the average specific activity of RW held in the storage facility.

Depending on the RW class and type, taking into account safety requirements, the decision on a particular type of disposal packaging is made. Each type has its own characteristics in terms of the external and internal volume of the container, as well as the average parameters of its filling capacity. The forecasts regarding waste generation and the parameters of the waste, as well as the characteristics of packages help to estimate the required number of purchased containers needed to accommodate the generated waste and to calculate the total external volume of all packages. The total

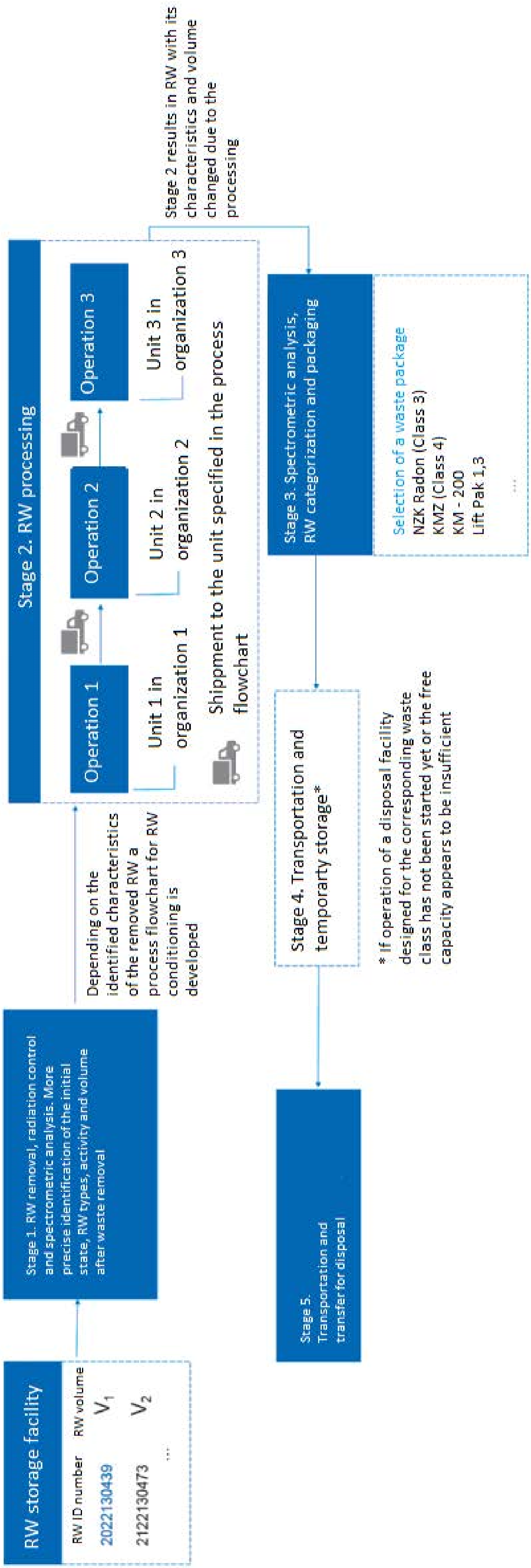


Figure 1. RW management flowchart used to calculate the total work cost

cost of containerization is calculated based on the purchase (market) cost per one container of a corresponding type, as well as the cost of relevant RW loading operations.

The costs at stages 4 and 5 are calculated based on the gross volume of the package. Transportation costs (by road or rail) are determined by the volume of transportation and the distance between the departure location and the destination. The rates are set by the transport company that is supposed to be involved in the transportation, or by the internal rates of the organization executing the contract (if it has its own capacity). The costs of temporary RW storage are estimated taking into account the tariff (rubles/m^3 year) of the organization accepting the waste for temporary storage. The cost of RW transfer for disposal is calculated taking into account the tariffs set by the Federal Antimonopoly Service [6].

As a result, based on the described procedure providing the identification of the total RW management costs, the main sources of uncertainty in the financial and economic model were identified:

1. Lack of information on the parameters of waste emplaced into a storage facility or differences between the actual and estimated parameters of the waste (type, condition, category), its activity and volume provided for under cost calculations.

2. Discrepancies between actual RW management operation flowchart and the planned one due to the discrepancy between the actual and expected parameters of the waste.

3. Uncertainties (variation) of the coefficients characterizing the change in the volumes and parameters of waste before and after a RW management operation.

4. Spread of specific activity levels for the generated RW at the pre-conditioning stage.

5. Uncertainty in the radionuclide content of RW (radionuclide composition), which complicates the forecasting of RW generation volumes predicted for each RW class.

6. Variation of the container filling capacity, and hence inaccuracies in the calculated amount of packaging required for RW isolation.

7. Uncertainty in the number of flights and trains necessary for waste transportation.

8. Risk of delay in the commissioning of RW disposal facilities or lack of free capacities in the repositories resulting in additional temporary storage costs.

9. Variations in the cost of resources and operations (market and financial risks).

10. Change in the value of money over time, which is relevant for long-term projects requiring the consideration of interest and inflation risks.

Application of probabilistic-statistical methods to assess the total work cost in the presence of various risks and initial data uncertainty

At the planning stage, input parameters for calculations may not be determined accurately, therefore making it impossible to obtain a specific reasonable estimate of the wok cost. In this regard, probabilistic-statistical methods may be recommended to consider the uncertainties and to provide interval cost estimates with a given probability.

This article proposes to assess the uncertainties based on the Monte Carlo Simulation method [7] providing possible distributions of economic estimates for a mathematical model with uncertain values of input parameters by setting the probability distributions of these parameters and, if necessary, indicating the relationship between them (correlation). To do this, a set of factors affecting the resulting indicator must be generated a large number of times according to the established probabilistic laws. The set of values obtained within one iteration is substituted into the model and the result is recorded. Ultimately, after a predetermined number of iterations, a sample is formed, which is subjected to statistical analysis: distribution estimates (functions and density), deviations, mathematical expectation, confidence intervals, etc.

This method is mainly challenged by the identification of distribution laws required to generate variable parameter values. Table 1 presents some recommendations on the selection of distribution laws formed based on evaluated practical experience in RW management and some hypotheses.

Interval assessment of RW management costs based on the example of a FSUE RADON's site (Sergiev Posad) considering the RW removal option

According to the data from the primary registration of RW and RW sites implemented in 2013—2014 under an additional contract supplementing the State contract No. N.4p.23.12.08.147 of February 19, 2008 Inventory Taking Aimed at Identifying the State of Nuclear and Radiation Hazardous Facilities and Development of Technical Solutions for Nuclear Industry Facilities (hereinafter, Primary Registration), the following RW storage facilities were available at FSUE RADON's site: KhTO No. 1—36 storage facilities, well-type storage facilities SBD 1 and SBD 2, BZ structure (complex of LRW tanks), building No. 69 and building 103. At the time of the Primary Registration (2013—2014), the amount of waste held in these facilities totaled some 130.3 thousand m^3. By 2020, under Federal Target Program Nuclear and Radiation Safety in

Table 1. Method used to generate values for various factors in the model supporting RW management cost assessment

Model Factor	Distribution law used to generate factor values in the model	Assessment method for the distribution law parameters
Unit costs of operations / costs / tariffs	Uniform distribution law with parameters $U(a; b)$	a – expected cost of work – 5 %; b – expected cost of work + 10 %
Radionuclide composition or proportion of a radionuclide that mainly contributes to a specified waste class	Uniform distribution law with parameters $U(a; b)$	Parameters a and b are determined by an expert taking into account the available engineering documentation and historical background information about the disposed RW
Shares of waste conditioned under a single process, if the structure of their ratio by type has not been unambiguously defined	Assuming that k options for RW conditioning process are available. For each of them, based on the uniform distribution $U(a_i; b_i)$, a share value is generated. The resulting set of values is normalized to comply with the restriction on the equality of the shares sum to 1	Parameters a_i and b_i, which characterize the range of RW share that was conditioned according to the i-th option are determined by an expert taking into account the available engineering documentation and historical background information about the disposed RW
Coefficient showing waste volume change after processing operation	Uniform distribution law with parameters $U(a; b)$ or lognormal distribution law with parameters $\log N(m; \sigma)$	Under the uniform law, a is the minimum value, b is the maximum value of the parameter determined experimentally; under log-normal law (if the distribution is asymmetric), the parameters m and σ are identified using the method of moments for confidence intervals of the coefficient distribution with a given probability determined experimentally
Container filling, %	Uniform distribution law with parameters $U(a; b)$	Parameters a and b are determined based on experimental data
Distribution of waste volumes by specific activity at the packaging stage	Lognormal law with parameters $\log N(m; \sigma)$ or selection of another distribution from a family of gamma distributions	m is the natural logarithm of the average RW specific activity in the SF according to the technical documentation; σ is the standard deviation for the lognormal distribution estimated based on the study of similar facilities

2016—2030 (hereinafter referred to as FTP NRS-2) and specifically under measure 8.1. Safe Removal of Radioactive Waste from Storage Facilities, RW Preparation for Disposal, Transportation to a Disposal Facility and Disposal, some waste was partially removed from FSUE RADON storage facilities and conditioned to meet waste acceptance criteria for disposal, including some 1,410 m^3 of RW from the BZ facility (operations performed under state contracts Д.4ш.244.20.18.1062 of December 14, 2018 and Д.4ш.244.20.18.1021 of March 6, 2018), and RW was also removed from KhTO No. 2.

A large amount of data on the FSUE RADON site (Sergiev Posad) was obtained while building an integral information model of the site, including 3D models of facilities and a three-dimensional detailed hydrogeological model of the site [8].

This site is of great interest in terms of the evaluated effectiveness of various RW management options, since, according to the Primary Registration, the decision on the waste accumulated there has the status of “a decision postponed until 2030.” This article presents the cost calculations for RW removal from the FSUE RADON site (Sergiev Posad), namely, from KhTO storage facilities No. 1—36, SBD-1 and SBD-2 well-type storage facilities and BZ structure (complex of LRW tanks). To implement the algorithm described above, the values presented in Table 2 were used as initial data [9].

Table 2. Input modeling parameters and approximate ranges of their variation (value indicators in 2019 prices) [9]

Volume breakdown by RW type (PTC step)	
RW breakdown by type for corresponding PTC*	**Interval**
KhTO № 1 – 29, 36	
Percentage of nonmetal RW removed from SF	70–85 %
Percentage of metal RW removed from SF, including those sent to:	15–30 %
fragmentation and pressing units	5–15 %
pressing units	70–90 %
repackaging	5–15 %
BZ structure	
Percentage of oil phase removed from SF	15–30 %
Percentage of LRW removed from SF	15–20 %
Percentage of SRW removed from SF	50–70 %
KhTO № 30–34	
Percentage of RW removed from SF in 200-l drums	15–30 %
Percentage of RW removed from SF in containers, including:	70–85 %
In leak tight packages	85–95 %
In packages requiring some maintenance	2–5 %
In damaged packages	3–10 %
Cost of RW management operations, without VAT	
Operation	**Specific cost, thousand RUB/m^3**
RW removal	4–88.5
Segregation	10–12.5

Continuation of Table 2

Operation	Specific cost, thousand RUB/m^3
Control measurements (weighting, dosimetric measurements, sampling and etc.)	0.5–1.4
Packaging (containerization)	8–10
Cementation	55–75
Fragmentation	50–70
Pressing	8–20
Certification	3–8
Container maintenance	9–11
SRW removal from wells	8–9
Oil phase pumping	25–29
Sampling and analysis of the oil phase	6.5–7.5
Pre-treatment of the oil phase before combustion	235–260
Certification of packages with oil phase	0.8–0.9
Oil phase combustion	155–175
Water phase conditioning (cementation)	60–75
Sampling and analysis	4–4.5
LRW evaporation	6–6.5
Weighing containers with solids	0.2
Dosimetric control of containers	0.55–0.6
Spectrometric control of containers	2.4–2.6
Conditioning of solid and liquid phases (cementation)	39–45
Decontamination of container outer surfaces with conditioned RW	0.4–0.5
Certification of packages with conditioned RW from BZ containers	9–11
Registration of acts for the acceptance and transfer of RW packages for storage	0.5–0.6
Average coefficients of RW volume increase for different processing operations	
Coefficient	**Value**
KIO* for cementing operation	1.3–1.5
KIO for joint grouting via cementation	1.1–1.2
KIO for the pressing operation	0.35–0.45
KIO for combustion operation	0.025–0.035
KIO for the evaporation operation	0.02–0.04
Container costs	
Package cost	**Cost, thousand RUB**
NZK-150-1.5P containers type	222–272
KMZ-RADON containers type	158–194
100-liter drums	1.9–2.4
Percentage of radionuclides in RW held in KhTO	
Radionuclide composition (mainly beta-emitting and transuranium radionuclides) was determined based on the study of historical records about the waste held in SF, the percentage fluctuation ranges were identified based on the data on the radioactive waste removed from KhTO No. 2 at FSUE RADON site in 2018	

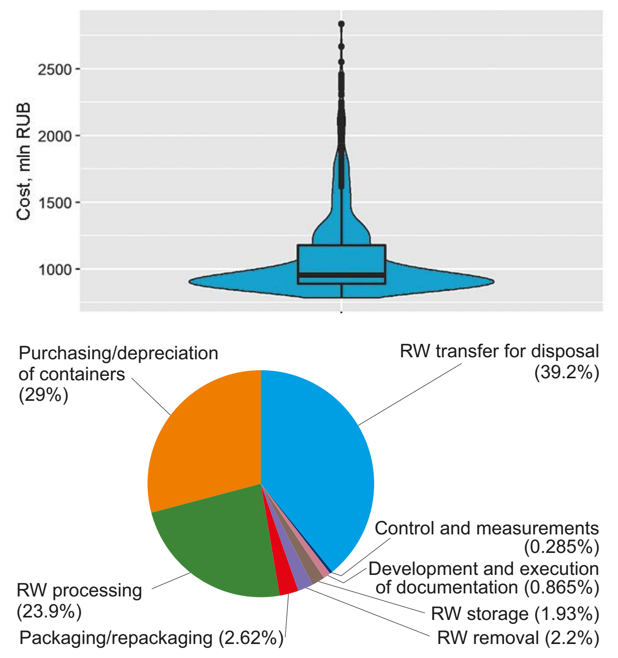
* PTC — production and technological cycle
* KIO — coefficient of change (increase) in the waste volume

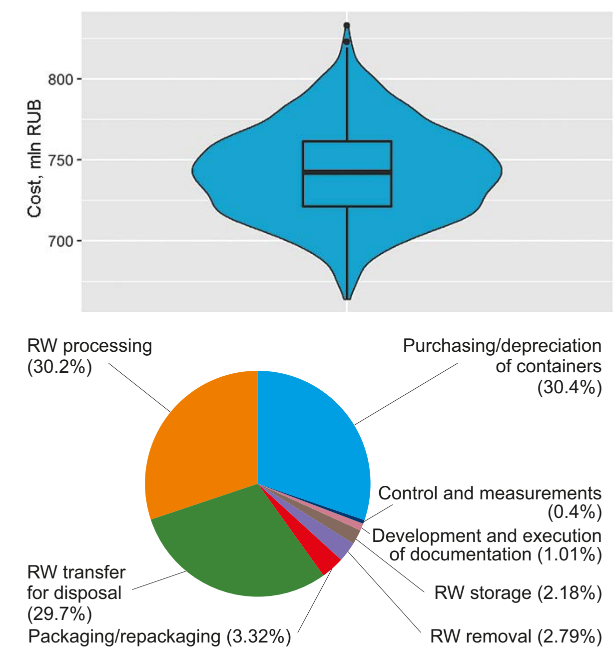
The results of waste removal from KhTO No. 2 were used as initial data to calculate the parameters showing the distribution of containerized RW volumes by the specific activity. The specific activity for the containers with removed RW was found to be ranging from 26 to 19,000 Bq/g with the largest amount of waste (about 85%) having its specific activity in the range from 100 to 900 Bq/g. Based on these data, the parameter σ was calculated for a log-normal distribution, which varied from 0.8 to 1.4 with a mathematical expectation of 1 with a 95 % confidence probability $\log N(m; \sigma)$, where the natural logarithm for the average specific activity of RW in a storage facility was used as the parameter m and the value estimated for KhTO No. 2 was used as the parameter σ.

Table 3 shows the modelled costs for RW removal from KhTO No. 8 and No. 21 at FSUE RADON not accounting for VAT and other deductions. The key factor affecting the uncertainty of the result depends on how close the average specific RW activity is to the threshold distinguishing different RW classes. The variation coefficient for KhTO No. 8 (the average specific activity of RW is close to the classification boundary between RW classes 3 and 4) is about 29.5 %, while for KhTO No. 21 (all removed RW will be definitely assigned to class 4) it amounts to some 5 %. This is due to a fairly large difference in the disposal cost between RW classes (in 2020, 158 thousand rubles/m^3 for class 3 and 49 thousand rubles/m^3 for class 4), as well as in the ratio between the internal and external volumes of packages designed for the disposal of different RW classes (the internal volume of NZK-150-1.5P container designed for RW Class 3 disposal is 1.5 m^3, its external volume is 3.74 m^3, the internal volume of KMZ-RADON container designed for RW Class 4 disposal is 3.1 m^3, its external volume is 3.835 m^3), which affects the final volume of RW transferred for disposal (the tariff is estimated per 1 m^3 of the external packaging volume). For KhTO No. 8 the share of costs associated with RW transfer for disposal and the purchase of containers under median scenarios amounts to ~70 %, and for KhTO No. 21 to ~60 %.

As a result, with a probability of 90 %, the total cost of RW removal from the FSUE RADON site (storage facilities No. 1—36 (except for KhTO No. 2), well-type storage facilities SBD-1 and SBD-2, structure BZ) is expected to range from 28.2 to 67.5 billion rubles in 2019 prices without VAT and various deductions accounted for; whereas the mathematical expectation was found to be equal to 42.1 billion rubles. The result obtained under conditions of high initial data uncertainty demonstrates the importance of preliminary stages necessary to refine

Table 3. Comparison of costs modelled for RW removal from KhTO No. 8 and No. 21, in 2019 prices*





KhTO №8	KhTO №21
Expected RW removal cost – 1,080 million rubles.	Expected RW removal cost – 750 million rubles.
Standard deviation of the cost – 320 million rubles.	Standard deviation of the cost – 28 million rubles.
Confidence interval – 90% from 838 to 1,790 million rubles.	Confidence interval – 90% from 700 to 800 million rubles.

*Not accounting for VAT and other deductions

the parameters and characteristics of RW held in the storage facilities and to improve the accuracy of cost assessments.

It seems interesting to consider the approaches used to build dynamic models and to provide the economic analysis of various decommissioning scenarios for storage facilities at FSUE RADON site. Below is considered a scenario suggesting annual removal of 2,000 m³ of RW starting from 2030. In this scenario, all RW will be removed from the considered storage facilities in about 70 years. Figure 2 shows the distribution of RW management costs over time under this scenario.

Further presented is a stress-test of this scenario in terms of RW processing and disposal infrastructure loading. Figures 3—5 show the load produced on the main RW processing facilities (90 % confidence intervals for RW volumes sent to these facilities). The pressing plant accounts for an average of 300 to 500 m³ per year for the periods of 2030—2041 and 2070—2103. The peak period is 2042—2069 (FSUE RADON has a Supercompactor pressing unit).

Fragmentation unit, on average, accounts for 40 to 70 m³ of RW per year, while during the peak period (2042—2069), the load can increase up to 100—120 m³/year. FSUE RADON has two RW fragmentation units with annual capacities of 250 and 740 m³/year. Figure 5 shows the loading of the cementing unit, which averages 1,500—2,500 m³/year.

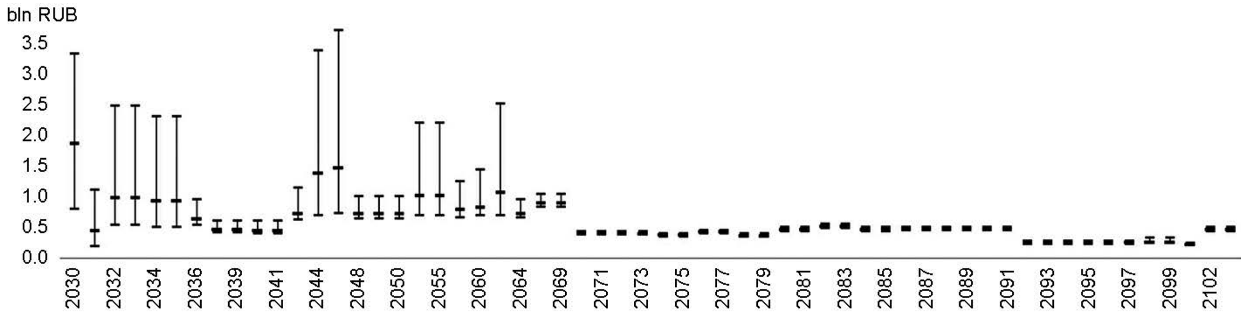


Figure 2. Breakdown of costs for RW removal from facilities at FSUE RADON site (90% confidence intervals)

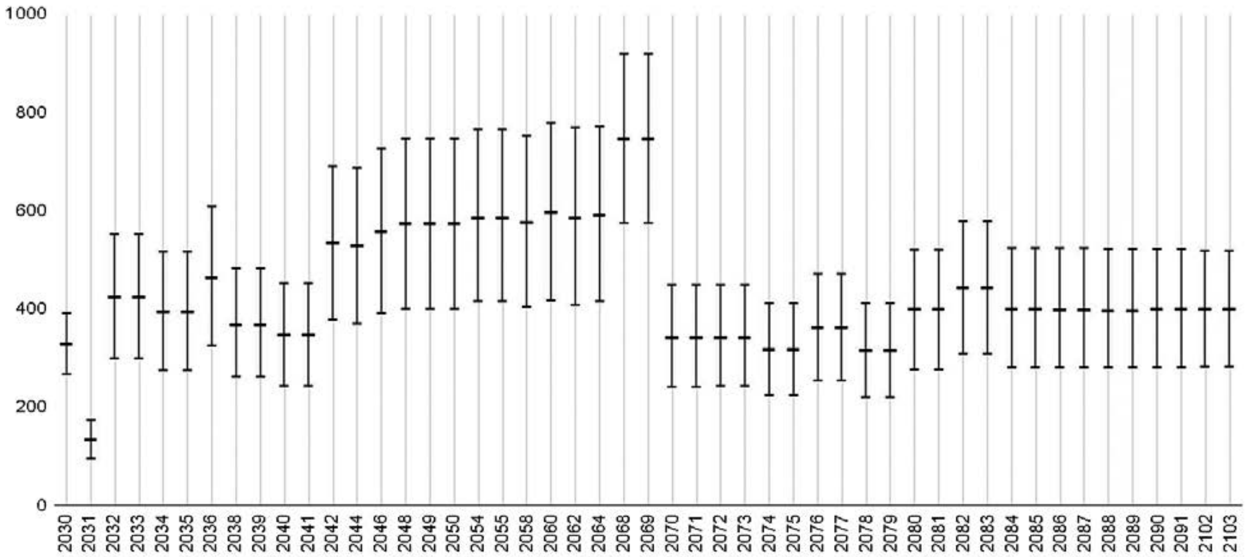


Figure 3. Expected load on the pressing unit by years (m³)

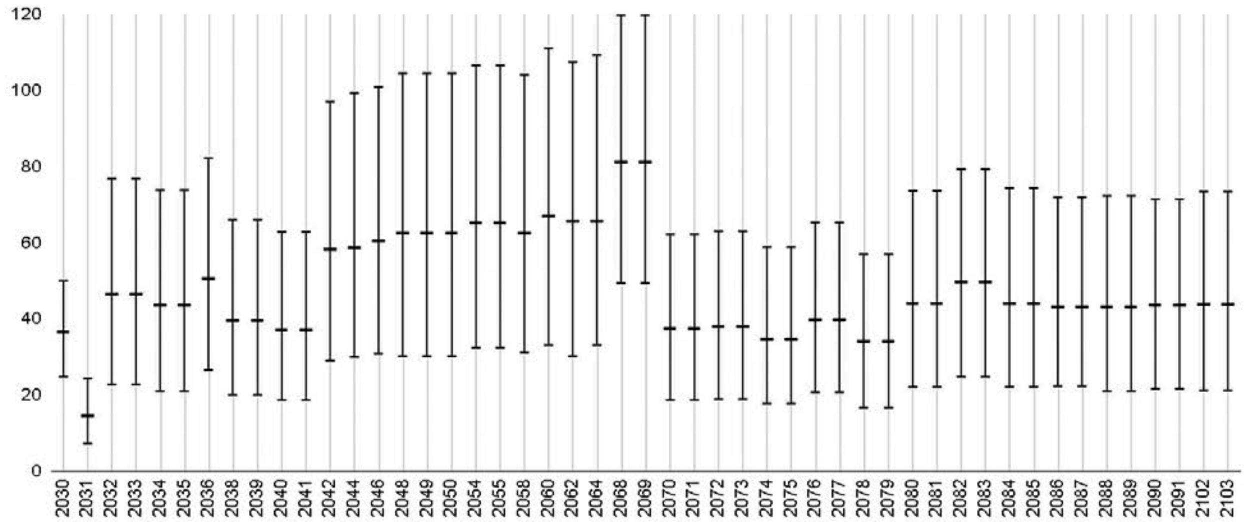


Figure 4. Expected load on the fragmentation unit by years (m³)

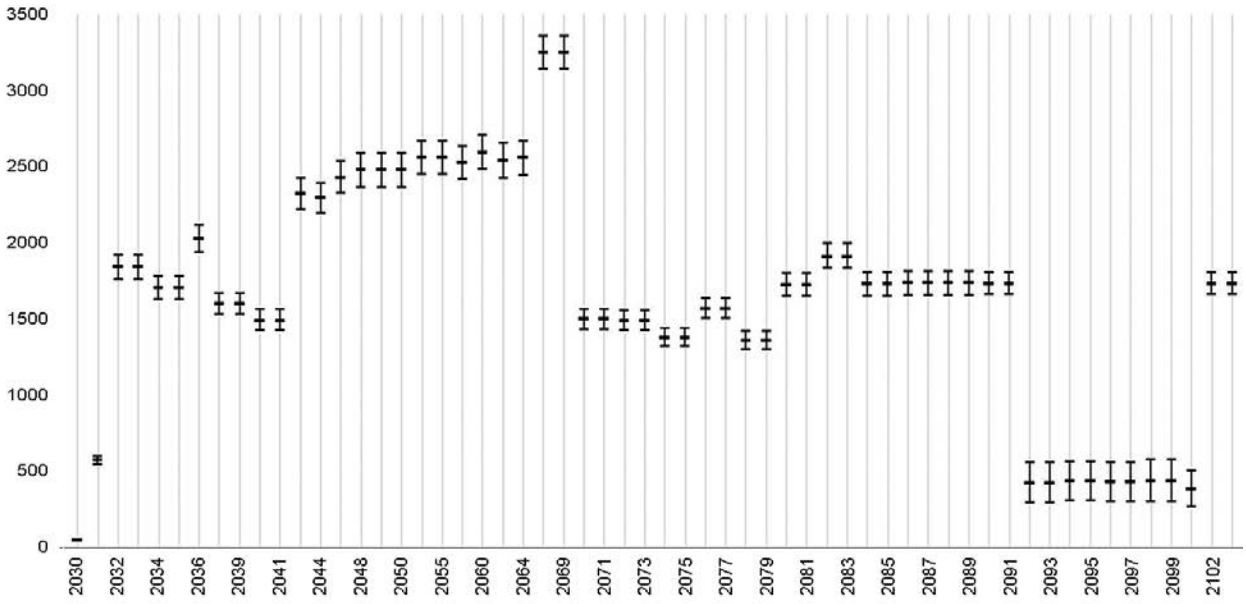


Figure 5. Expected load on the cementation unit by years (m³)

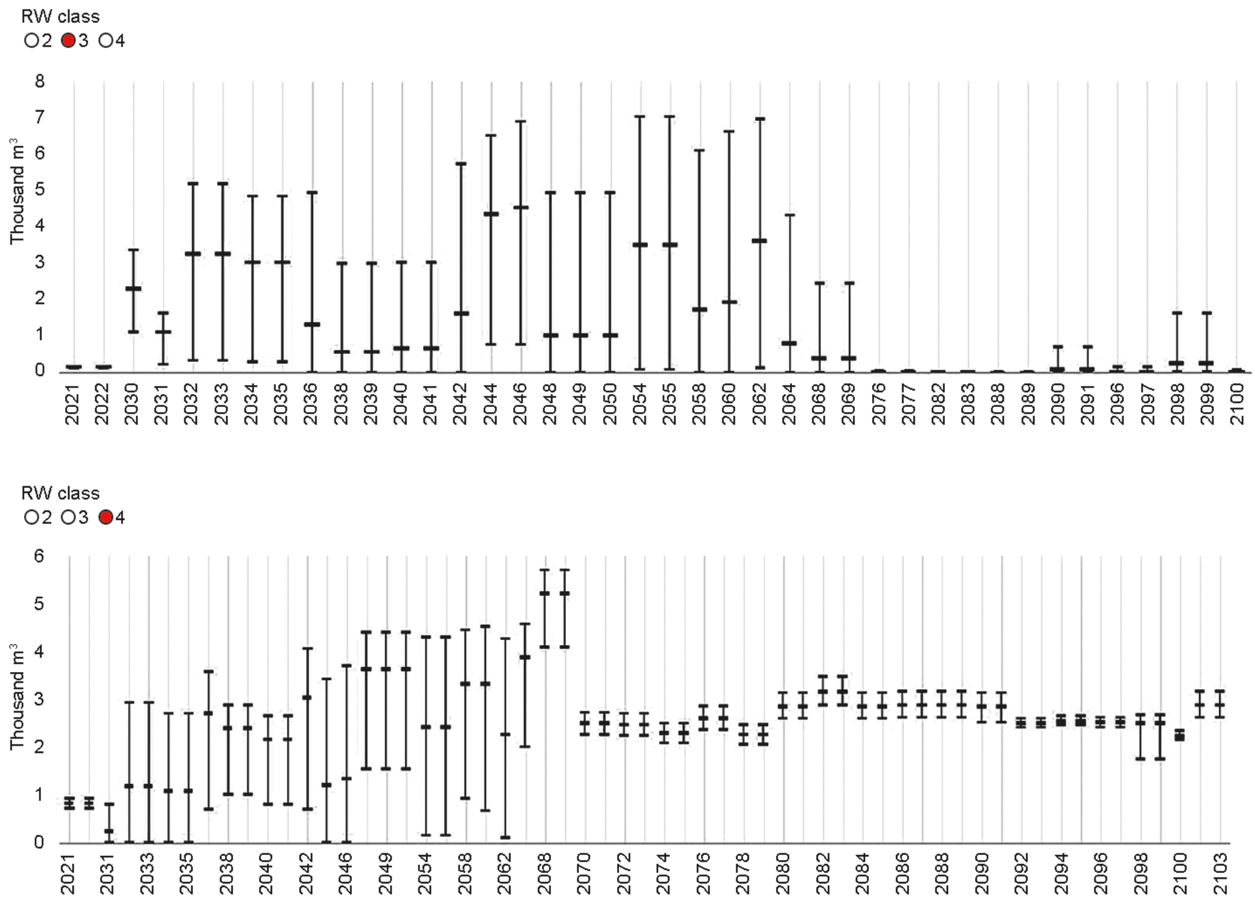


Figure 6. Forecasted generation of waste (by class) intended for disposal (m^3)

The greatest load falls on 2069—2070, when the volume of RW supplied for processing reaches 3.3 thousand m^3/year. The miniblock mortar mixing plant at FSUE RADON has a maximum capacity of 5,540 m^3/year, and taking into account the current workload, the average free capacity is about 2,500 m^3/year. Thus, if the enterprise maintains the current performance level in terms of RW conditioning at other sites, then there is a risk that the plant's capacity appears inadequate to process the RW removed from the storage facilities at FSUE RADON site. Therefore, taking into account the conducted stress testing of the infrastructure and its loading, it was recommended to adjust the RW removal schedule for 2040—2070.

Figure 6 shows the calculated RW volumes intended for transfer to disposal. In 2030-2100, the (expected) gross volume of RW transferred for disposal will amount to about 150,000 m^3 of RW Class 4 and 25,000 m^3 of RW Class 3. About 700 pieces of KMZ-RADON containers and 200 pcs. of NZK are required on average per year to condition the removed RW. If a decision is made on RW removal from the FSUE RADON site, these volumes should be taken into account in the development of new disposal facilities.

Conclusion

The approaches to financial and economic planning used under the study assuming the initial data uncertainty and based on Monte Carlo modeling method provide the opportunities for reasonable interval assessments of:

- RW management costs;
- RW processing infrastructure loading (volume of waste that is required to be processed using a specific facility or technology);
- number of purchased disposal containers by types;
- volume of RW packed for disposal by class.

Our findings demonstrate the high sensitivity of the total RW management costs to the initial RW parameters, in particular, the radionuclide composition. Therefore, additional studies are essential since they help to clarify the initial RW parameters, thereby, minimizing uncertainties before relevant financial and economic plans are developed.

Findings of the statistical analysis focused on RW disposal cost assessment considering specific storage facilities and dynamic modeling may be expediently used in the stress testing performed to check the adequacy of RW processing and disposal infrastructure, as well as to plan its further development.

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