COMPARATIVE COST ANALYSIS OF RADIOACTIVE WASTE MANAGEMENT OPERATIONS IN THE RUSSIAN AND INTERNATIONAL MARKETS

Ilyasov D. F., Ivanov A. Yu., Kuznetsova E. O., Budunova A. S., Stepanyan P. O., Mikhailenko A. A.

Nuclear Safety Institute of the Russian Academy of Sciences, Moscow, Russia

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The article provides an overview of costs associated with radioactive waste management activities in different countries in the following areas: treatment, packaging, storage, transportation, and disposal of radioactive waste. All data were brought to a comparable form using various economic and mathematical methods in order to make a correct comparative analysis. In conclusion, the results of cost comparison across countries are presented, the possible reasons for their deviations are discussed.

Keywords: *cost of operations, costs, radioactive waste management, comparative analysis, classification of radioactive waste, economic and mathematical methods, radioactive waste.*

This study aims to compare the cost of radioactive waste management operations in the Russian and international markets allowing to assess the objectivity and reasonableness of costs associated with relevant operations in the territory of the Russian Federation and to determine the potential for cost reduction. To achieve this goal, data on the cost of radioactive waste management operations in various countries that could be found in open sources were collected and systematized, certain methods were applied to bring the costs to a comparable form with a comparative analysis performed and relevant results summarized.

The high-level cost estimates by countries and their comparison presented in the article can be viewed as the first step of a comprehensive study. The study aimed at standardizing the RW management processes and identifying their correct market value in the regions of Russia to solve the problems of long-term cost planning, to reserve the required amount of funds and ensure sustainable funding of this activity. It should be noted that a structural analysis of costs for different countries would provide more correct conclusions about the reasons of the cost discrepancy. However, its implementation appears quite problematic due to the secrecy of detailed information and its unavailability in open sources.

Collection and processing of initial information on the cost of RW management operations and its reduction to a comparable form

Data on the cost of RW management operations in different countries were collected and systematized based on the information from open literature sources since such information is commonly considered as a commercial secret and the specialized organizations refused to provide it upon our request. Thus, some 50 foreign sources were studied: relevant data have served a basis for cost estimates performed either by direct or indirect

methods for the following areas of interest: RW processing, packaging, storage, transportation and disposal.

This study features the data on the US, Germany, Great Britain and Italy. In order to provide correct comparison with Russian costs, the following comparison procedures were performed:

1. The units of measurement used in different countries (for example, dollar/cubic foot; dollar/gallon) have been converted to the ones familiar for Russia (rubles/cubic meter). For reference: 1 m^3 = = 35.315 ft^3, 1 m^3 = 264 gal. The foreign currency rate was taken at the level of average annual values for 2019: 1 USD = 64.66 RUB; 1 € = 72.41 RUB; 1 GBP = = 82.55 RUB; 1 AUD = 44.98 RUB [8].

2. All cost estimates from various sources relevant for the year t (t < 2019) were reduced to the cost level of 2019 by increasing them considering the accumulated inflation rate according to the data provided by national statistics bodies of the corresponding countries for the period between t and 2019.

3. To account for the changes in the cost of RW management operations over time in different countries caused not by the inflation process (i. e., by a change in the value of the money stock), but by the increased or reduced cost of the technologies themselves, the calculations were based on the assumption that this factor, on average, can change the cost by ± 1 % per year. Thus, when bringing the cost to the level of 2019 calculated is the confidence interval, in which the upper and lower bounds can be defined as follows:

$$P^{vg}_{2019} = P_t \cdot I_t^{2019} \cdot (1.01)^{2019-t},$$
$$P^{ng}_{2019} = P_t \cdot I_t^{2019} \cdot (0.99)^{2019-t} \quad (1)$$

where P^{vg}_{2019}, P^{ng}_{2019} are the upper and the lower margins for the transaction cost as of 2019, P_t is the transaction cost indicated in the source as of year t, I_t^{2019} is the accumulated inflation index in the country for the period from t to 2019 calculated based on relevant resources [9, 10].

Reports of organizations executing state contracts dealing with RW conditioning according to the acceptance criteria for disposal, as well as requests to RW management organizations were considered as the main sources of data on the cost of RW management operations in Russia.

The cost of RW management operations is highly dependent on the RW type, its current state and category. In this regard, it seems reasonable to take a closer look at RW classification systems available in the considered countries to increase the validity of the cost comparison and to form better conclusions. The criteria used in different countries for waste categorization as radioactive were described in detail in [1].

Specific aspects of RW classification in different countries

Figure 1 presents RW classification system introduced in the US. In contrast to the classification system commonly applied in Russia, commercial RW is divided into HLW and LLW, which, in turn, are further subdivided into classes A, B, C, GTCC (greater than class C with a specific activity higher than the one of class C). It should be noted that the American commercial RW classification system takes into account waste origin and is based on the principle suggesting that the responsibility for the final stages of RW management (radioactive waste disposal) is split between DOE (US Department of Energy) and NRC (US Nuclear Regulatory Commission). This approach to RW classification has been criticized for many years. For example, many American experts point out that the very name of the category "low-level waste" can be misleading. In fact, RW class C is comparable by its activity to the category commonly designated as ILW in the Russian Federation, and LLW of the GTCC class have an activity comparable to the one of high-level RW [1].

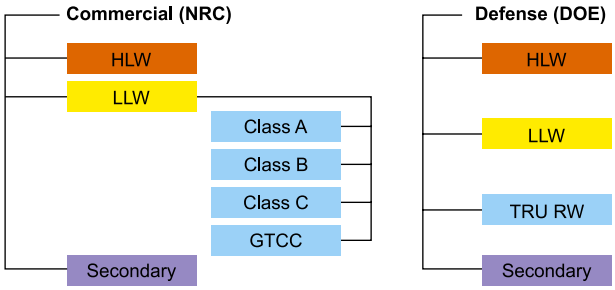

Figure 1. RW classification system in the US

Earlier in Germany, radioactive waste was classified into three categories depending on the specific activity level: HLW, ILW and LLW. The new classification provides for RW subdivision into two classes — heat-generating RW and RW with negligible heat generation (Figure 2) [1].

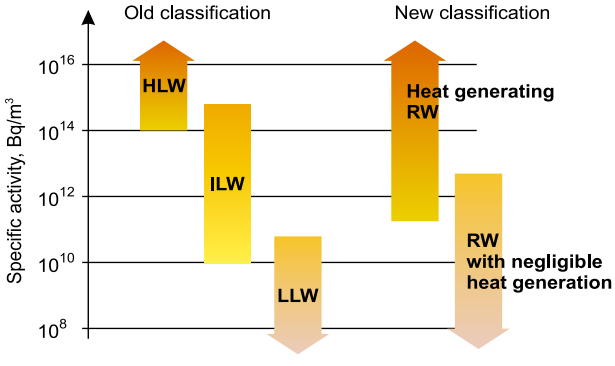

Figure 2. RW classification system in Germany

RW classification in the UK is most similar to the one adopted in Russia with 4 categories of waste that can be distinguished: HLW, ILW, LLW and VLLW.

In Italy, RW classification system involves three categories of waste depending on its characteristics and the concentration of radionuclides:

Category I stands for the waste the characteristics of which are similar to those indicated as VLLW according to the international classification.

Category II stands for the waste the characteristics of which are similar to those indicated as short-lived LLW according to the international classification. Category II waste involves the waste which will decay to radioactivity level of few hundreds of Bq/g within a few decades or centuries.

Category II, in turn, is subdivided into two subcategories:

1) solid waste, the activity of which is below the established limits. This type of waste can be disposed of without conditioning;

2) waste, the activity of which is higher than the established limits. This type of waste cannot be disposed of without conditioning.

Category III stands for the waste the characteristics of which are similar to those indicated as ILW and HLW according to the international classification [2].

Under this study the costs of operations were mainly compared for the waste deemed as LLW and ILW according to Russian RW classification system (namely, LLW category in the USA (classes A, B and C), RW with negligible heat generation in Germany, LLW and ILW in the UK, categories I and II in Italy).

Unit cost analysis

RW processing

RW processing usually makes up the largest part of the total cost associated with the full RW conditioning cycle allowing to bring the waste in accordance with the acceptance criteria for disposal. Unit cost estimates of RW processing were presented in the report of the US Argonne National Laboratory Unit Costs of Waste Management Operations [3]. Table 1 provides a comparison between the unit costs for RW processing operations in Russia and the US. Unit values for each operation cover quite a wide range, since they have a fairly high scattering depending on the facility and RW type. But even taking this factor into account, based on the data from Table 1, one can see that the unit cost of RW management operations in the United States is several times higher than in Russia.

Table 1. Unit cost of RW processing operations in the US and Russia

Operation	US			RF	
	RW category	Unit cost as of 1994, $/ft^3	Unit cost as of 2019, thousand RUB/m^3	RW category	Unit cost as of 2019, thousand RUB/m^3
Compaction	LLW	105	323–529	LLW/ILW	Up to 500
Incineration	LLW	424	1,303–2,138	LLW/ILW	150–460
Fragmentation	LLW	145	446–731	LLW/ILW	50–115
Solidification (cementation)	LLW	346	1,063–1,745	LLW/ILW	20–115
Melting (metal)	LLW	568	1,745–2,864	LLW/ILW	70–90
Evaporation	-	-	-	LLW/ILW	70–80
Compaction	TRU	105–158	323–796	-	-
Solidification (cementation)	TRU	164–257	504–1,295	-	-
Incineration	TRU	630–1,050	1,936–5,294	-	-

Packaging

Table 2 summarizes the data on the costs of containers used for RW management in different countries. It shows that within one category of RW, the cost of a foreign container appear to be very heterogeneous. For example, in Italy, the range of container costs for LLW varies from 50,000 up to 12 million RUB, in the UK for ILW containers — from 3 to 12 million RUB. In Germany, container cost for RW with negligible heat generation (equivalent to LLW and ILW according to the international classification) is about 500,000 RUB.

Russian containers, similar to the European ones, are characterized with a fairly wide range of costs, but in general their cost appears to be orders of magnitude lower. Table 3 exemplifies the cost of some containers according to the data from the public procurement portal of the Russian Federation [12]. Thus, the cost of containers for LLW and ILW belonging to the 3rd class, varies from 120,000

Table 2. Container costs in different countries as of 2019 (per piece)

Container	Internal volume, m^3	External volume, m^3	Cost per piece, thousand RUB	RW type/category	Country
1000-l drums	1	1.68	54–78	LLW with no conditioning required	Italy [4]
Containers 3.7 m^3	3.7	5.2	4,809-6,953	Metal LLW trequiring conditioning	Italy [4]
Containers 8.2 m^3	8.2	10.8	8,416-12,168	Non-metal LLW requiring conditioning	Italy [4]
Gusscontainer	3.1	5.4	9,218-13,327	ILW and HLW	Italy [4]
DAW Drums	0.22	0.25	12-17	Compacted	Italy [4]
Containers accepted by RWDF Konrad	–	-	515–547	RW with negligible heat generation – LLW and some ILW	Germany [5]
Metal (stainless steel) unshielded container	2.8	3.7	3,846-4,084	ILW	UK [6]
Cast iron protective container DCIC	2.4	3.7	11,966-12,706	ILW	UK [6]
Reinforced concrete protective container	5	11.9	2,564-2,723	ILW	UK [6]
Cast iron protective container DCIC	8.7	10.7	10,256-10,891	ILW	UK [6]

Table 3. Container costs in the Russian Federation according to [12] (per piece)

Purchase No.	Customer	Container type	Information about RW	Internal volume, m^3	Cost, thousand rubles
32009374703, 32009195147, 31908727946, 31908421056	JSC Rosenergoatom Concern	Container MK-0.2	Highly concentrated crystallized radioactive waste (LRW)	0.20	22.9–25.2
32009193151, 32008939420, 31908713846	JSC SSC RIAR FSUE Atomflot, FSUE FEO	Containers of NZK-150-1.5P type	LLW/ILW of Class 3	1.50	177–189.6
32009237885, 32008882645	JSC Rosenergoatom Concern	Container NZK-150-1.5P 345 MZ	LLW/ILW of Class 3	1.50	279.1–314.2
32009237885	JSC Rosenergoatom Concern	Container NZK-150-1.5P L.65.555.00.000	LLW/ILW of Class 3	1.50	124.3–162.6
31908593839	JSC Rosenergoatom Concern	Container KRAD-1.36	Class 4	1.40	69.6
32009193151, 32008868037	JSC SSC RIAR FSUE FEO	Metal container protective KMZ	LLW/ILW of Class 3	3.10	176.1–246.2
32008853932	FSUE Atomflot	Purpose-designed container PU-2STK-SK option A	LLW	30.00	978
32009062498, 32008942771	FSUE FEO	Reinforced concrete containers	LLW/ILW of Class 3	1.50–1.90	158.3–189.6

to 320,000 rubles, the cost of a RW container for RW Class 4 amounts to some 70,000 rubles.

Temporary storage

The cost of RW temporary storage largely depends on the type of a storage facility. Table 4 shows the estimated unit costs (tariffs) for RW storage depending on the type of the storage facility in the Russian Federation. Average estimated cost of temporary storage in the Russian Federation accounts for 3,500 rubles per 1 cubic meter of radioactive waste.

Table 4. Estimated tariffs for RW storage in the Russian Federation as of 2019

SF type	Tarif, RUB/m^3
Purpose-designed buildings	1,185
Containers and tanks	3,500
Structures with engineered safety barriers	193

According to [5], storage of 1 m^3 of ILW or LLW would cost about 29,000 RUB in Germany. In the

United States, the storage cost of 1 m³ of HLW can vary from 20,000 to 200,000 RUB depending on the storage capacity. A trench storage facility would cost about 300,000—800,000 RUB/m³; if remote waste handling methods are applied, the cost can be up to 5 million RUB/m³ (Table 5).

Table 5. RW storage tariffs in the US as of 2019 [3]

Technology	Category	Cost, RUB/m³
Storage in drums ($26 \cdot 10^6$ gal)	LLW, HLW	126,000– 207,000
Storage in drums ($60.8 \cdot 10^6$ gal)	LLW, HLW	80,000– 132,000
Storage in drums ($2.75 \cdot 10^6$ gal)	LLW, HLW	21,000– 34,000
Storage in a trench SF, non-remote treatment	TRU	323,000– 529,000
Storage in a trench SF, remote treatment	TRU	165,000– 5,193,000

Transportation

In the UK, the estimated transportation cost for 1 cubic meter of RW accounts for some 108,000—115,000 RUB [6]. For comparison, Table 6 shows the transportation tariffs applied in the US depending on the transportation distance.

Table 6. Transportation costs in the US as of 2019

Distance	Cost, RUB/m³
Up to 500 km one way	3,000–8,000
500-800 km one way	7,000–12,000
No less than 800 km one way	9,000–15,000

Estimates regarding RW transportation costs in the Russian Federation have shown that the unit cost varies considerably depending on the route. At the same time, specific patterns governing the changes in the unit transportation costs per 1 m³ of RW and per 1 km of the total route distance were revealed neither for the Russian Federation nor for the US. Estimated transportation costs in the Russian Federation for 1 m³ of RW fall within the range of 7 to 90 rubles per 1 km, the average cost for 1 m³ of RW amounts to some 20—30 rubles per 1 km. Thus, on average, the transportation of 1 m³ of RW at a distance of 600 km will require about 12,000—18,000 rubles, which is approximately 50 % more expensive than in the United States.

Disposal

Table 7 summarizes the RW disposal costs in several countries depending on RW category.

The estimated RW disposal costs have a fairly high level of variability. In the Russian Federation, LLW category can correspond to the 4th or 3rd class of RW with disposal tariffs accounting for 46,000 RUB/m³ and 152,000 RUB/m³ respectively as of 2019 (see Table 8). ILW disposal cost in the UK ranges from 300,000 to 1,000,000 RUB/m³, in the US it ranges from 400,000 to 1,000,000 RUB/m³ for HLW. In the Russian Federation, the disposal cost for RW Class 1 and 2 (HLW, some ILW) amounts to 1.5 million RUB/m³ and 600,000 RUB/m³ respectively.

Under this study based on the analysis of various international and national projects, RW

Table 7. RW disposal costs in different countries as of 2019

RW category/class	RW DF technology/type	Country	Cost, RUB/m³
LLW that should be conditioned		Italy [4]	572–827
LLW, Class A, building structures (e.g., concrete, scrap metal, etc.)	Disposal of RW from decommissioning	USA [7]	149–186
LLW, class A large components	Disposal of RW from decommissioning	USA [7]	613–763
LLW, Class B and C	Disposal of RW from decommissioning	USA [7]	7–9
LLW	Shallow trenches	USA [7]	43–862
LLW	Concrete structures	USA [7]	209–343
LLW	Surface disposal facilities	USA [7]	387–635
LLW	Underground disposal facilities	USA [7]	584–958
LLW	Concrete containers	USA [7]	630–1,034
LLW	Trenches of a storage facility with engineered barriers	USA [7]	750–11,002
ILW, disposal in unshielded containers	Disposal in unshielded containers	UK [6]	895–951
ILW, disposal in shielded containers	Disposal in shielded containers	UK [6]	335–356
HLW		USA [3]	383–957
TRU	Shallow surface trenches	USA [3]	301–2,027
TRU	Deep geological disposal	USA [3]	1,936–3,933

Table 8. RW disposal tariffs in the Russian Federation as of 2019

RW Class	Type of a disposal facility	Cost, RUB/m³
1	Deep geological disposal facility	1,424
2	Deep geological disposal facility	662
3	Near-surface RW disposal facility	152
4	Near-surface RW disposal facility with less stringent requirements	46

management costs were also compared accounting for the full cycle of waste conditioning in accordance with waste acceptance criteria for disposal. Table 9 shows that the difference between the cost of RW management operations commonly performed under European nuclear decommissioning projects may differ by several orders of magnitude. Thus, in Switzerland and the UK ILW management costs are 2—4 times higher than in the Russian Federation, whereas in Sweden the cost is quite similar.

Table 9. Benchmarking the costs for ILW management [11]

Country	Cost as of 2015, thousand AUD/m³	Cost as of 2019, thousand RUB/m³
Switzerland	43.99	2,031–2,112
Sweden	15.83	731–760
UK	36.94	1,706–1,774
Russia	-	450–990

Conclusion

Based on the comparison of estimated RW management costs for Russia and other countries, the following conclusions can be drawn:

- RW processing cost is on average 5—15 times higher in the US than in Russia, although the difference can be even higher due to the fact that practically the entire RW inventory is processed in the US whereas in Russia only a limited RW inventory is subject to processing given the available processing technologies;
- packaging cost in Germany is 2—4 times higher, in Great Britain and Italy is 2—30 times higher than in the Russian Federation;
- RW temporary storage cost in the US is 6—60 times higher than in the Russian Federation, whereas in Germany it is approximately 8 times higher, which to some extent may be due to differences in the storage quality requirements;
- RW transportation: unit cost accounting for the transportation of 1 cubic meter of radioactive waste per 1 km in the Russian Federation is more expensive than in the US — the difference accounts for some 50 % amounting to 20—30 rubles per m³/ km;
- RW disposal cost: on average relevant costs in the US are 2—8 times higher and in the UK 2—7 times higher than in the Russian Federation.
- High differentiation of the costs can be explained by the following factors:
- the wage fund, which usually amounts to 30—50 % of the service fee, is an order of magnitude higher in other countries compared to the Russian Federation.
- the cost of energy resources (fuel, electricity) in the Russian Federation is significantly lower in comparison with Western countries;
- differences in methods applied and safety requirements, which can reduce the correctness of the comparison (it's hard to get more detailed information since it's considered classified);
- instability of the Russian ruble and significant inflation in the Russian economy in 1995—2016 due to which the reliability of monetary unit comparison accounting for different years was reduced dramatically.

Similar discrepancies can be also traced in related industrial sectors: the level of wages and the cost of energy resources largely affect the difference between the unit cost estimated for national and foreign markets. For example, according to the official financial statements of PJSC LUKOIL and Royal Dutch Shell PLC (hereinafter referred to as Shell), companies' personnel costs in 2019 amounted to about $ 3.2 billion (indicator "personnel costs") and $ 13.2 billion (indicator "total employee costs"), respectively. Taking into account the rationing of this indicator by production volumes (PJSC LUKOIL — 876 MMbbloe/year, Shell — 1,332 MMbbloe/yeawr), the ratio between Russian and European unit costs for payroll accounts for 2 : 5. Considering that PJSC LUKOIL is widely represented on a global scale, the difference in the ratio of unit costs for payroll "within the Russian Federation" and the European ones may appear be even more sizable.

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Information about the authors

Ilyasov Damir Fatovich, PhD in economics, Scientific Researcher, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: idf@ibrae.ac.ru.

Ivanov Artem Yurievich, Head of Department, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: aivanov@ibrae.ac.ru.

Kuznetsova Ekaterina Olegovna, junior researcher, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: kuznetsova@ibrae.ac.ru.

Budunova Anastasiya Sergeevna, engineer, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: budunova@ibrae.ac.ru.

Stepanyan Polina Olegovna, engineer, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: spo@ibrae.ac.ru.

Mikhailenko Anastasiya Andreevna, engineer, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: mikhaylenko@ibrae.ac.ru.

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