# WASTE-SPECIFIC VOLUME FOR RETROSPECTIVE, PREDICTIVE ASSESSMENTS, AND RANKING OF PRACTICES DURING NORMAL OPERATION OF RUSSIAN NUCLEAR POWER PLANTS

by

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**Possibilities of applying the generated radioactive waste-specific volume per unit of produced electricity are shown. This waste specific volume is used for retrospective assessment and forecasting of radioactive waste volumes generated at Russian nuclear power plants. According to the available data period covering 2008-2021, the mean and median values of the annual waste-specific volume for each nuclear power plant were obtained. The medians for solid radioactive wastes divided into the categories of very low-level wastes, low-level wastes, intermediate level wastes and high-level wastes are equal to $3.6 \cdot 10^{-2}$, $3.2 \cdot 10^{-2}$, $3.2 \cdot 10^{-3}$, $3.0 \cdot 10^{-4}$ $m^3(GWh)^{-1}$, respectively. For liquid radioactive wastes of the low-level waste and intermediate level waste categories – $1.3 \cdot 10^{-3}$ $m^3(GWh)^{-1}$, $2.4 \cdot 10^{-2}$ $m^3(GWh)^{-1}$, respectively. The highest mean and median values of waste-specific volume for all radioactive waste categories are typical for nuclear power plants with LWGR (RBMK) reactor installations. The forecast based on the plans to increase electricity production by Russian nuclear power plants indicates a likely increase in the volume of radioactive waste generation by 0.7-7.4 % (depending on the waste category) in the period from 2022 to 2027. The waste-specific volume use makes it possible to rank the existing practices of nuclear power plant operation by the volume of radioactive waste generation to justify the criteria for compliance with the International Project on Innovative Nuclear Reactors sustainability methodology.**

*Key words: radioactive waste, waste-specific volume, reactor facility, nuclear power plant, innovative nuclear reactor*

## INTRODUCTION

The widespread application of technologies based on radioactive substances (RS) and nuclear materials is determined by the unique opportunities or alternatives for obtaining demanded services or products. Further development and extension of nuclear energy use should not threaten the need of future generations to preserve a favorable environment [1]. Radioactive waste (RW) is a specific factor with long-term negative impact on the environment, which always accompanies the use of radioactive and nuclear materials. Safety for humans and the environment when handling RW at all stages of the life cycle, including the time-limited stage of final isolation, in many ways determines the acceptability of the risks nuclear energy uses in the present and future. According to the national Russian Federation requirements, control and accounting are required at each stage of handling RW and RS [2]. The data on the annual RW generation of each category allows us to adequately predict the volume of RW generation for a long-term period and prepare the infrastructure of facilities for RW disposal in advance [3].

During the normal operation of a nuclear power plant (NPP), the main sources of RW generation are the replacement of worn-out materials and equipment elements and structures containing RS, decontamination of rooms and equipment, and technological media cleaning from RS. The physical and chemical properties of RW are determined by the structure and condition of the RW materials, the technological conditions of their application, and the methods of handling during generation and accumulation. The categories and classes of RW formed at NPP depend on the aggregate state and the specific activity of the radionuclide structure [4-6]. Basic information on the classification of radioactive waste in the Russian Federation is presented in several regulatory documents [7-9].

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During the entire operation of NPP in Russia, a significant amount of RW has been accumulated in specialized storage facilities located on the territory of the stations. Newly generated and accumulated RW are registered by NPP specialists [10-12]. The volume of annual RW generation ($m^3$ per year) information during normal operation of NPP is presented in the annual reports on environmental safety for the period 2008-2021, shown on the website of Rosenergoatom Concern [13]. The content of environmental reports involves safety culture aspects such as quantitative and qualitative characteristics of all factors affecting the population and the environment during normal operation of NPP, including data on the management of RW. The published information is characterized by incompleteness. For instance, data integrity on all RW categories ranges from 19 % for Beloyarsk NPP to 86 % for Smolensk NPP [14]. Under the assumption of representativeness, it is possible to retrospectively reproduce the missing data to estimate the total amount of generation of each RW category for the considered period based on information on the annual electricity production of each NPP [15]. The key element for such estimates is the specific waste rate of each category of RW generation for each GWh of electricity produced. The numerical values of the waste-specific volume allow us to compare the volumes of RW generation at different NPP over time, regardless of the type and capacity of the reactor installations used, as well as to obtain estimates of each category of RW generation in the future based on electricity production plans. The dimension of the waste-specific volume is $m^3(GWh)^{-1}$ for liquid (LRW) and solid (SRW) radioactive waste. It demonstrates the scale of their annual generation against the background of annual electricity production and allows us to conclude environmental efficiency in the field of RW management at Russian NPP. The waste-specific volume is a convenient criterion for comparing existing practices of RW generation at NPP. The application of this indicator allows us to rank the ecological performance of NPP in the following categories: *best, sustainable,* and *worst* practices of RW generation at NPP. The results of this ranking allow us to obtain quantitative criteria for assessing the compliance of new NPP projects with the principles of sustainability of national energy systems set out in the International Project on Innovative Nuclear Reactors (INPRO) methodology [16]. To implement the basic principle of the INPRO methodology, the values of the waste-specific volume of the designed power units RW volume must not exceed the values of the waste-specific volume corresponding median value of the *best* practices currently operating at NPP. In this paper, based on the published environmental Rosenergoatom Concern reports period covering 2008-2021, the possibility of retrospective recovery of missing data on the volumes of RW generation for the selected time interval is demonstrated. This demonstration is given both for all NPP as a whole, and taking into account NPP with a given type of reactor installations. Also, using waste-specific volume, forecast estimates of the RW generation are given, taking into account the plan for electricity production at NPP in Russia. These estimates can be considered targets for each category of RW generation.

## MATERIALS AND METHODS

### Calculation of normalized measure and retrospective assessment of the volume of RW generation at Russian

A retrospective assessment of the annual generation of RW can be made based on the results of statistical processing of data on the volume of annual generation of each category of RW ($m^3$ per year), not reduced to electricity production. The main disadvantage of this approach is that it ignores important characteristics of reactor plants, such as power and operation factors. The use of normalized measures eliminates this disadvantage. The normalization of the annual volume of generation of each category of RW per unit of electricity produced makes it possible to correctly combine or compare subsamples of data on nuclear power plants with reactor installations of different power. To calculate the normalized measures of RW generation at Russian NPP, the following steps are performed:

- the sample of electricity production data [GWh] for each NPP for each year in the period 2008-2021 was formed as the sum of electricity produced by each NPP power unit, according to the PRIS (IAEA) database [15],
- the subsamples of available data on the annual generation of LRW and SRW [$m^3$] of each category of RW were formed based on the materials of published environmental reports of Russian NPP [13], and
- for each NPP, subsamples of the ratio of the annual volume of each category of RW to the annual electricity production, $m^3(GWh)^{-1}$ for each year of the considered period are formed.

To formalize the calculations and analysis of the obtained data, the following symbols are introduced: $V$ [$m^3$] – the volume of annual RW generation, $E$ [GWh] – annual electricity production, and $S$ [$m^3(GWh)^{-1}$] – the normalized measure of the generation of each category of RW. The calculation of the required $S_{ijk}$ value for the $i$-th NPP is performed using all available data of the $j$-th category of RW for the $k$-th year of observation

$$S_{ijk} \quad \frac{V_{ijk}}{E_{ijk}} \tag{1}$$

The obtained medians of normalized measures $\langle S_j \rangle$, tab. 1, allow us to perform a retrospective assessment of the volume of $\langle V_{jik} \rangle$ generation of four cate-

**Table 1. Descriptive statistics of annual specific waste rate of RW generation by waste categories at Russian NPP period covering 2008-2021**

| RW categories | Number of values | $\bar{S}_j$ [m$^3$(GWh)$^{-1}$] | Standard deviation | $<S_j>$ [m$^3$(GWh)$^{-1}$] | Minimum [m$^3$(GWh)$^{-1}$] | Maximum [m$^3$(GWh)$^{-1}$] | Ratio $\bar{S}_j/<S_j>$ |
|---|---|---|---|---|---|---|---|
| LRW | | | | | | | |
| LLW | 18 | $1.4\cdot10^{-3}$ | $4.5\cdot10^{-4}$ | $1.3\cdot10^{-3}$ | $2.0\cdot10^{-4}$ | $2.7\cdot10^{-3}$ | 1.1 |
| ILW | 58 | $3.4\cdot10^{-2}$ | $1.9\cdot10^{-2}$ | $2.4\cdot10^{-2}$ | $3.6\cdot10^{-3}$ | $1.3\cdot10^{-1}$ | 1.4 |
| SRW | | | | | | | |
| VLLW | 15 | $9.8\cdot10^{-2}$ | $9.7\cdot10^{-2}$ | $3.6\cdot10^{-2}$ | $8.1\cdot10^{-3}$ | $2.7\cdot10^{-1}$ | 2.7 |
| LLW | 73 | $6.1\cdot10^{-2}$ | $5.6\cdot10^{-2}$ | $3.2\cdot10^{-2}$ | $7.1\cdot10^{-4}$ | $5.4\cdot10^{-1}$ | 1.9 |
| ILW | 72 | $6.0\cdot10^{-3}$ | $4.8\cdot10^{-3}$ | $3.2\cdot10^{-3}$ | $1.2\cdot10^{-4}$ | $4.0\cdot10^{-2}$ | 1.9 |

gories of SRW and two categories of LRW for each NPP for any year in the studied interval of 2008-2021 as follows

$$V_{ijk} \quad E_{ik} \; S_j \tag{2}$$

This assessment does not apply to a specific NPP but applies equally to all operational NPP in Russia. This means that the calculated values $<V_{jik}>$ do not adequately reproduce the volume of RW at a particular plant, but are used only to estimate the total volume of each category of RW for all NPP for a single year $<V_{jk}>$ and for the entire period under review $<V_j>$

$$V_{jk} \qquad {}_i \; V_{ijk} \tag{3}$$

$$V_j \qquad {}_k \; V_{jk} \tag{4}$$

### Determination of frequency distributions quartile ranges of Russian NPP waste-specific volume

The criteria for the implementation of the basic principle of optimization and sustainable development of nuclear energy INPRO can be determined based on the studied NPP classification into three categories: the best, sustainable, and worst practice of radioactive waste management. The categories of NPP can be defined as follows. First, the boundaries of the frequency distributions quartile ranges of waste-specific volume, based on the set of all the studied NPP for the period from 2008 to 2021, are calculated. Then, according to the time series of annual waste rates $Q_{i,j}$, m$^3$(Gwh)$^{-1}$ each $i$-th station for the $j$-th year a rank depending on the correspondence to the quartiles can be assigned ($q_1$ – 25$^{th}$ percentile, $q_2$ – 50$^{th}$ percentile (median), and $q_3$ – 75$^{th}$ percentile)

$$R_{i,j} \quad \begin{matrix} 1, & if & Q_{i,j} \quad q_1, \\ 2, & if & q^1 \quad Q_{i,j} \quad q_3, \\ 3, & if & Q_{i,j} \quad q_3, \end{matrix} \tag{5}$$

The rank values $R_i^{av}$ averaged over the entire observation period for each station indirectly indicate the frequency of failing $Q_{i,j}$ within corresponding quartiles and allow classifying NPP by the required categories. The categories boundaries by average ranks are determined expertly and are taken 1-1.5 for the best ($Q_{i,j}$ are more often in the 1st quartile), 1.5-2.5 – for stable (2$^{nd}$ and 3$^{rd}$ quartiles) and 2.5-3 – for the worst (mainly 4$^{th}$ quartile) practices. This approach was used in works [17, 18].

## RESULTS AND DISCUSSIONS

In the period covering 2008-2021, electricity production at Russian NPP increased by 33.5 %. In 2021 year, 202 939 GWh was produced, and in 2008 – 152 058 GWh, the total increment amounted to 50 882 GWh, fig. 1. The contribution to the electricity production increase was made by NPP with PWR (VVER) reactor unit – 47 424 GWh (93.2 %) and with FBR (BN) reactor unit – 3 458 GWh (6.8 %). The total amount of power production for the period under review is 2 462 191 GWh [15].

A continuous increase in electricity production, except for 2013 and 2020, is likely to be accompanied by an increase in annual RW generation. The assump-

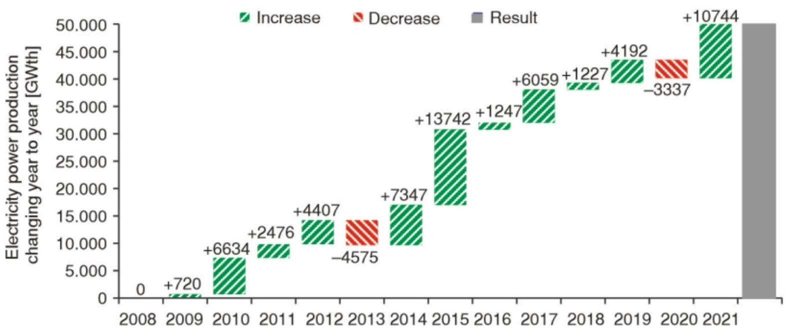


**Figure 1. Dynamics of electricity production at Russian NPP from 2008 to 2021 [10]**

tion of a comparable increase in the production of RW of all categories cannot be refuted or confirmed based on fragmentary annual data published in the environmental reports of NPP [9]. However, it is possible to obtain more correct estimates of the volume of annual generation of LRW and SRW by retrospectively reproducing (interpolating) the values missing in the environmental reports. For this purpose, the waste-specific volume ($S_{ijk}$) for typical Russian reactor installations is calculated in this study.

Each $S_{ijk}$ value is specific and characterizes the volume of generation of a specific category of RW: low-level waste (LLW) and intermediate-level waste (ILW) for LRW; very low-level waste (VLLW), low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW) in a particular year at a particular NPP for each GWh of electricity produced. The complex of values ($S_{ijk}$) describes all possible variants of the values of normalized measures in general, without taking into account the type and power of reactor installations. The main statistical characteristics of the normalized measures of the volume of RW generation at Russian NPP, calculated from the entire available data set for the period covering 2008-2021, are presented in tab. 1.

In the reviewed environmental reports lack information about the LRW generation of the VLLW category since this category is not provided in the Russian RW classification [7-9]. Information on the generation LRW of the HLW category is either not available or indicates zero values of annual generation.

The mean values – $\overline{S}_j$ of specific waste rates of all categories of RW exceed the corresponding median values $< S_j >$, which indicates the asymmetry of the frequency distributions of the studied values, so it is more correct to use the medians as indicators for retrospective and predictive estimates of the generation of RW since they are more resistant to statistical outliers in the analyzed sample data.

Figure 2 shows the structure of SRW categories by the total volume of RW generated at Russian NPP, according to the data available in environmental reports and obtained by retrospective assessment for the entire study period.

According to environmental reports for SRW, the contribution of each category is ranked as follows: LLW > VLLW > ILW > HLW with multiple LLW predominance. In terms of the total volume of LRW, there is a multiple predominance of ILW (97 %) over LLW (3 %).

The results of a retrospective assessment of both the missed values and the values registered in the environmental reports of the annual production volumes of each category of RW for the period under review showed an expected increase of 33.5 %, in proportion to the increase in electricity production. At the same time, the structure of LRW and SRW differs from the one that was obtained from the available public reporting data fig. 2(a). In the total volume of LRW, the share of ILW was 95 %, which approximately corresponds to the analysis of published data shows. The contribution of each category of waste to the total volume of SRW changed multidirectional: increased by 38 % for VLLW, decreased by 32 % for LLW, decreased by 5 % for ILW, and decreased by more than 1 % for HLW fig. 2(b).

The values of the medians $< S_j >$ in tab. 1 are obtained from all available data, but without taking into account the possible specifics of the generation of RW at NPP with different types of reactor units. The given specifics can be ignored only if the share of each station in the total volume of power generation at the NPP is preserved. However, in a period covering 2008-2021, the growth of electricity production was 68.8 % at PWR (VVER) and 91.5 % at FBR (BN), and reduction was 13.2 % at LWGR (RBMK) reactors, so for a retrospective assessment, it is necessary to take into account the normalized measures of the RW generation at NPP with one type of reactor. Despite the limited set of initial data subgroups of the values of waste-specific volume for the types of reactor installations were formed and their median values $< S_j >$ type were obtained, tab. 2.

The data in tab. 2 clearly show that NPP with LWGR (RBMK) reactor units generate more RW of all categories except LLW of LRW one producing the same amount of electricity at NPP than PWR (VVER) and FBR (BN). A retrospective estimate of the volume of RW generation, taking into account the type of reactor unit $<W_{jik}>$ type, can be obtained according to the formula (2) using $< S_j >$ type instead of $<S_j>$. The total volumes of each category of RW for all NPP with one type of reactor unit for a single year $<W_{jik}>_{\text{type}}$ and for the entire period 2008-2021 $<W_j>_{\text{type}}$ is calculated using eqs. (3) and (4), respectively.

Taking into account the specifics of the median values of $<S_j>$ type, the total volume of LRW $<W_j>$ type up by 11 % and by 79 % for SRW, tab. 3.

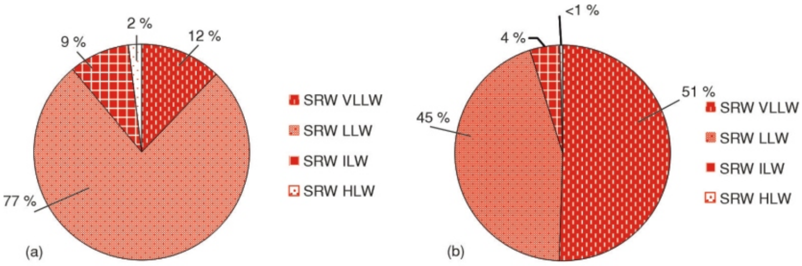


**Figure 2. Structure of SRW categories by volume of generated waste at all Russian NPP period covering 2008-2021; (a) according to environmental reports [13] and (b) obtained by retrospective assessment**

**Table 2. Median values of waste-specific volume of RW generation, $m^3(GWh)^{-1}$, for NPP with different types of reactor units $< S_j >$ type**

| | LRW | | | SRW | | |
|---|---|---|---|---|---|---|
| Type of reactor unit | LLW | ILW | VLLW | LLW | ILW | HLW |
| LWGR (RBMK) | $1.3 \cdot 10^{-3}$ | $4.0 \cdot 10^{-2}$ | $2.1 \cdot 10^{-1}$ | $5.5 \cdot 10^{-2}$ | $4.7 \cdot 10^{-3}$ | $7.1 \cdot 10^{-4}$ |
| PWR (VVER) | $2.2 \cdot 10^{-3}$ | $1.8 \cdot 10^{-2}$ | $1.5 \cdot 10^{-2}$ | $1.9 \cdot 10^{-2}$ | $2.1 \cdot 10^{-3}$ | $2.3 \cdot 10^{-5}$ |
| FBR | – | $2.7 \cdot 10^{-2}$ | – | $7.7 \cdot 10^{-3}$ | – | $7.2 \cdot 10^{-5}$ |

**Table 3. Retrospective assessment of the volume of each category of SRW and LRW generated at all Russian NPP period covering 2008-2021**

| Method of assessment | Volume SRW [$m^3$] | | | | Volume LRW [$m^3$] | | | |
|---|---|---|---|---|---|---|---|---|
| | VLLW | LLW | ILW | HLW | Total SRW | LLW | ILW | Total LRW |
| Without taking into account the type of reactor unit $<W_j>$ | $8.82 \cdot 10^4$ | $7.78 \cdot 10^4$ | $7.83 \cdot 10^3$ | $7.37 \cdot 10^2$ | $1.75 \cdot 10^5$ | $3.28 \cdot 10^3$ | $6.02 \cdot 10^4$ | $6.35 \cdot 10^4$ |
| Taking into account the type of reactor unit $<W_j>_{type}$ | $2.27 \cdot 10^5$ | $7.95 \cdot 10^4$ | $7.38 \cdot 10^3$ | $7.11 \cdot 10^2$ | $3.14 \cdot 10^5$ | $4.34 \cdot 10^3$ | $6.60 \cdot 10^4$ | $7.03 \cdot 10^4$ |
| $<W_j>_{type} / <W_j>$ | 2.57 | 1.02 | 0.94 | 0.96 | 1.79 | 1.32 | 1.10 | 1.11 |

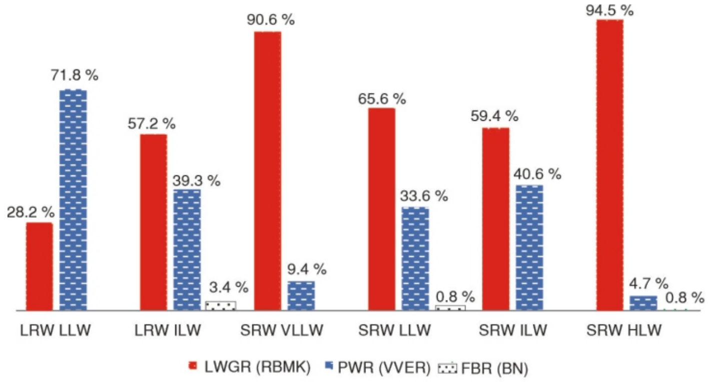


**Figure 3. Share of RW at NPP with a given type of reactor unit in the total volume for each category of RW**

The volume of LRW of the LLW category is less by 32 % and by 10 % of the ILW category in comparison with the retrospective assessment without taking into account the type of reactor unit; the volume of SRW of the LLW category changes multidirectional.

Despite a significant increase in electricity production at PWR (VVER) reactor units (93.2 %) and FBR (BN) (6.8 %) in the period covering 2008-2021, the bulk of RW of each category (except LRW of category LLW) formed during this period falls on NPP with LWGR (RBMK) plants, fig. 3.

Since there was no growth of power generation at LWGR (RBMK) reactors during this time, it can be expected that the increase in the total RW volumes of all NPPN, calculated retrospectively taking into account the normalized measures for different types of reactors, will not be proportional to the increase in electricity production (33.5 %). In particular, our calculations show that the volume of waste has increased from 2008 to 2021 as follows: LRW of LLW category - 41.9 %; LRW of ILW category 17.8 %; SRW of VLLW category – 6.7 %; SRW of LLW category – 5.2 %; SRW of ILW category – 14.2 %. Category HLW of SRW has decreased by 9.7 %. In the long run, the replacement of LWGR (RBMK) reactor plants with PWR (VVER) will be accompanied by a reduction in RW volumes while maintaining the achieved level of electricity production.

According to the plans for the nuclear power industry of the Russian Federation development, the amount of electric power generation by NPP NPPs located on the territory of Russia in 2027 – at least 221.7 billion kWh per year [19]. Thus, electricity production will grow by 9.3 % relative to 2021. When using the median values of $<S_j>$ normalized measures of RW generation without taking into account the type of reactor installation, tab. 1, the forecast estimate of waste volumes in 2027 will be 5.72 $10^3$ and $1.57 \cdot 10^4$ $m^3$ for LRW and SRW, respectively. By 2027, the volume of each category of RW will grow in proportion to the growth of electricity production by 9.3 %. tab. 4.

To predict the volume of RW generation, taking into account the median values of normalized measures $<S_j>_{type}$ specific for each type of reactor (tab. 2), it is assumed that the entire growth of electricity production will occur at NNP with PWR (VVER) reactors, and the electricity production at RBMK and FBR will remain unchanged – 57.8 billion kWh and 7.2 billion kWh per year, respectively [12].

By 2027, the volumes will increase by 0.7-7.4 %, depending on the category of RW, tab. 4.

In general, both approaches give approximately the same result of the forecast for the total volume of RW in 2027:

– LRW without taking into account the type of reactor – $5.72 \cdot 10^3$ $m^3$, taking into account – $5.64 \cdot 10^3$ $m^3$;

**Table 4. Forecast assessment of volumes of each category of RW $<W_j>$ and $<W_j>_{type}$ at all Russian NPP 2027**

| Year | Volume LRW [$m^3$] | | | Volume SRW [$m^3$] | | |
|---|---|---|---|---|---|---|
| | LLW | ILW | VLLW | LLW | ILW | HLW |
| $<W_j>$ (2021) | $2.70·10^2$ | $4.96·10^3$ | $7.27·10^3$ | $6.42·10^3$ | $6.45·10^2$ | $6.07·10^1$ |
| $<W_j>$ (2027) | $2.95·10^2$ | $5.42·10^3$ | $7.94·10^3$ | $7.01·10^3$ | $7.05·10^2$ | $6.63·10^1$ |
| $<Wj>_{type}$ (2021) | $3.74·10^2$ | $5.01·10^3$ | $1.47·10^4$ | $5.82·10^3$ | $5.57·10^2$ | $4.50·10^1$ |
| $<W_j>_{type}$ (2027) | $4.02·10^2$ | $5.24·10^3$ | $1.48·10^3$ | $6.06·10^3$ | $5.84·10^2$ | $4.53·10^1$ |
| Volume increase [%] | 7.4 | 4.6 | 1.3 | 4.1 | 4.8 | 0.7 |

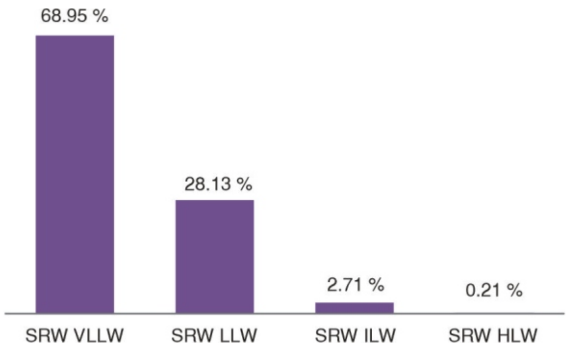


**Figure 4. Forecast assessment of the structure of solid RW categories by the volume of waste generated at all Russian NPP in 2027**

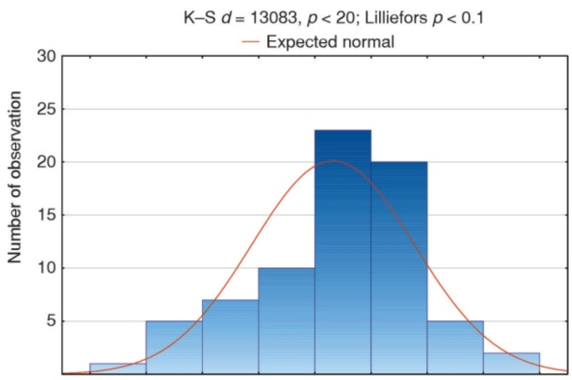


**Figure 5. Frequency distribution of logarithms of the waste-specific volume of SRW LLW category with a the oretical normal curve**

– SRW without taking into account the type of reactor – 1.57 $·10^4$ $m^3$, taking into account – $2.15·10^4$ $m^3$.

In 2027, the volume of LRW by 93 % will consist of the category of ILW. The structure of SRW by RW categories expected in 2027 is shown in fig. 4.

More than 97 % of the predicted volume of SRW in total for all nuclear power plants will belong to the category of VLLW and LLW.

## Determination of frequency distributions quartile ranges of Russian NPP specific waste rate

Percentiles $q_1$, $q_2$, and $q_3$ of frequency distributions of waste-specific volume at Russian NPP NPP for 2008-2021 were calculated separately for two categories of LRW and four categories of SRW, tab. 5.

Since the reporting data is characterized by a large number of gaps, the estimates given may have some statistical bias. To reduce this effect, it seems appropriate to obtain quartile estimates from the corresponding theoretical curves of the best approximations of the frequency distributions of waste-specific volume. The analysis of the data under consideration showed the presence of a positive skew of the waste-specific volume of each category. The hypothesis of a normal distribution of values in all cases was rejected according to the Kolmogorov-Smirnov and Shapiro-Wilk criteria; the lognormal distribution law turned out to be the best approximation. As an example, fig. 5 shows the frequency distribution of logarithms of the waste-specific volume of the SRW LLW category from 2008 to 2021 as the most representative sample among all the studied populations. It can be seen that according to the Shapiro-Wilk criterion, the hypothesis about the normality of logarithmic values cannot be rejected, therefore, the assumption about the lognormal distribution of the initial data is valid (in this case, the lognormal approximation is the most preferable of all studied).

**Table 5. Percentiles and frequency distributions quartile ranges of waste-specific volume at Russian NPP according to the reporting data of 2008-2021**

| Radioactive waste category | $q_1$ (25th percentile) [$m^3(Gwh)^{-1}$] | $q_2$ (median) [$m^3(Gwh)^{-1}$] | $q_3$ (75th percentile) [$m^3(Gwh)^{-1}$] | Quartile range ($q_3 - q_1$), [$m^3(Gwh)^{-1}$] |
|---|---|---|---|---|
| LRW LLW | $1.13\ 10^{-3}$ | $1.33\ 10^{-3}$ | $1.53\ 10^{-3}$ | $4.01\ 10^{-4}$ |
| LRW ILW | $1.72\ 10^{-2}$ | $2.45\ 10^{-2}$ | $4.15\ 10^{-2}$ | $2.42\ 10^{-2}$ |
| SRW VLLW | $1.49\ 10^{-2}$ | $3.58\ 10^{-2}$ | $2.18\ 10^{-1}$ | $2.03\ 10^{-1}$ |
| SRW LLW | $9.03\ 10^{-3}$ | $3.16\ 10^{-2}$ | $5.67\ 10^{-2}$ | $4.77\ 10^{-2}$ |
| SRW ILW | $2.07\ 10^{-3}$ | $3.18\ 10^{-3}$ | $6.71\ 10^{-3}$ | $4.64\ 10^{-3}$ |
| SRW HLW | $3.16\ 10^{-5}$ | $2.99\ 10^{-4}$ | $7.60\ 10^{-4}$ | $7.28\ 10^{-4}$ |

**Table 6. The values of percentiles and quartile ranges of waste-specific volume restored on the basis of the lognormal approximation of the frequency distributions of the initial data**

| Radioactive waste category | $q_1$ (25th percentile) [m$^3$(Gwh)$^{-1}$] | $q_2$ (median) [m$^3$(Gwh)$^{-1}$] | $q_3$ (75th percentile) [m$^3$(Gwh)$^{-1}$] | Quartile range ($q_3 - q_1$), [m$^3$(Gwh)$^{-1}$] |
|---|---|---|---|---|
| LRW LLW | 8.23 $10^{-4}$ | 1.23 $10^{-3}$ | 1.84 $10^{-3}$ | 1.02 $10^{-3}$ |
| LRW ILW | 1.72 $10^{-2}$ | 2.69 $10^{-2}$ | 4.22 $10^{-2}$ | 2.50 $10^{-2}$ |
| SRW VLLW | 1.95 $10^{-3}$ | 4.70 $10^{-2}$ | 1.13 $10^{-1}$ | 9.35 $10^{-2}$ |
| SRW LLW | 9.53 $10^{-3}$ | 2.53 $10^{-2}$ | 6.73 $10^{-2}$ | 5.77 $10^{-2}$ |
| SRW ILW | 1.48 $10^{-3}$ | 3.26 $10^{-3}$ | 7.19 $10^{-3}$ | 5.71 $10^{-3}$ |
| SRW HLW | 4.25 $10^{-5}$ | 1.67 $10^{-4}$ | 6.54 $10^{-4}$ | 6.12 $10^{-4}$ |

The obtained lognormal approximation of the frequency distributions of the initial data allows us to give *theoretical* estimates of the percentiles of waste-specific volume, which could be expected with the complete absence of gaps in the studied populations, tab. 6.

In order to increase conservativeness, the main criterion for compliance with the basic INPRO principle is the median value of waste-specific volume for the best practices of operating NPP. Accordingly, for the implementation of this principle, it is necessary that the values of the waste-specific volume of the projected power units do not exceed the values of the medians of the waste-specific volume of the *best* practices currently operating at NPP. However, at present, there is not enough initial data to obtain a stable assessment of the boundary between the best and worst practices of RW generation at Russian NPP.

Since the completeness of the reports in most cases does not exceed 50 %, it is not possible to correctly calculate the values $R_i^{av}$ ranks averaged over the observation period for each station, and accordingly classify the NPP to required categories. To obtain stable boundaries, it is proposed to use the percentiles of the frequency distributions of waste-specific volume reconstructed by the lognormal approximation. At the same time, the value of the lower quartile $q_1$ of the corresponding RW category can be taken as the INPRO compliance criterion. The choice of the lower quartile, which is essentially the boundary of the *best practices* category, as the main guidelines for the design of new NPP reactor installations fully corresponds to the basic principle of the INPRO methodology, since it ensures that the radiation impact of RW generation is not exceeded in comparison with the current experience of operating NPP.

## CONCLUSIONS

Information about the volume of RW annual generation of Russian NPP, presented in the public environmental reports of Rosenergoatom Concern JSC period covering 2008-2021, is fragmentary. This does not allow us to adequately assess the structure of RW by category and make a firm conclusion about an increase or decrease in the volume of their generation, taking into account a significant electricity production increase (by 33.5 %). At the same time, the available data allow us to obtain mean and median values, as well as quartile ranges of frequency distributions of a waste-specific volume of two categories of LRW and four categories of SRW for each NPP.

For compliance with the basic principle of the INPRO methodology, projects of new NPP reactor installations should have waste-specific volume no worse than values of the lower boundary of the *best practices* category, m$^3$(GWh)$^{-1}$:
– for LRW LLW – 8.23 $10^{-4}$,
– for LRW ILW – 1.72 $10^{-2}$,
– for SRW VLLW – 1.95 $10^{-2}$
– for SRW LLW – 9.53 $10^{-3}$,
– for SRW ILW – 1.48 $10^{-3}$, and
– for SRW HLW – 4.25 $10^{-5}$.

The application of the obtained waste-specific volume will allow the introduction of new criteria for an independent assessment of the sustainable development of nuclear energy in Russia. If the contribution of each NPP to the total amount of electricity produced is constant, retrospective and forecast estimates of the volume of RW generation can be performed without taking into account the type of reactor installation using the median values of the entire sample formed. In this case, the estimate of the change in the volume of any category of RW will exactly correspond to the change in electricity production. However, taking into account the tendency for a significant increase in electricity production at PWR (VVER) reactor plants and almost fixed annual production at LWGR (RBMK) and FBR (BN), it is advisable to use median values of the waste-specific volume to each type of reactor plant, especially since the analysis showed multiple excesses of the waste-specific volume of any category at NPP with LWGR (RBMK) reactors compared to PWR (VVER) and FBR (BN). The waste-specific volume application for each type of reactor installation leads to an increased retrospective assessment of the volume of LRW and SRW for the period covering 2008-2021 and a comparable forecast estimate for 2027 in comparison with the waste-specific volume use without taking into account the type of reactor installation. Both over the past period and in the future until 2027, the main volume of all categories of LRW and SRW is formed at NPP with

LWGR (RBMK) reactors. In perspective, the replacement of LWGR (RBMK) installations with PWR (VVER) will be accompanied by a decrease in the volume of RW while maintaining the achieved level of electricity production.

## AUTHORS' CONTRIBUTIONS

D. D. Desyatov – creation of the initial database, statistical and data analysis, presentation of results; A. A. Ekidin – introduction and discussion of the results; K. L. Antonov – choice, justification, and application of statistics information analysis methods; V. A. Shatalin – collection of up-to-date information and updating of the database.

## REFERENCES

[1] ***, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO, Manual, Vol. 1-9, IAEA-TECDOC-1575/Rev.1, IAEA, Vienna, 2008
[2] ***, Federal Rules and Regulations in the Filed of Nuclear Energy Use „Basic Rules on Accounting and Control of Radioactive Materials and Radioactive Waste in an Organization" (in Russian), NP-067-16: Approved by Order of the Federal Environmental, Industrial and Nuclear Supervision Service No 503, November 28, 2016
[3] ***, Status and Trends in Spent Fuel and Radioactive Waste Management. Nuclear Energy Series. No. NWT- 1.14, IAEA, International Atomic Energy Agency, Vienna, 2018, p. 74
[4] Desyatov, D. D., *et al*., The Current Classification of NPP Disposable Solid Radioactive Wastes in Russia Analysis, *Phys. Atom. Nuclei, 83* (2020), March, pp. 1507-1513
[5] Desyatov, D. D., *et al*., Radioactive Waste Classification in the Russian Federation and the USA, *Phys. Atom. Nuclei, 83* (2020), March, pp. 1625-1632
[6] Ivanov, E. A., *et al*., Actual Problems of Classification of Solid Radioactive Wastes to be Disposed, Generated in Atomic Energy Use, *Yad. Radiat. Bezopasn., 88* (2018), 2
[7] ***, Federal Law of the Russian Federation No. 190-FZ of 11.07.2011 (in Russian), as Amended by the Federal Law No. 188-FZ of 02.07.2013
[8] ***, Decree of the Government of the Russian Federation (in Russian), No. 1069 of 19.10.2012, as Amended by the Decree of the Government of the Russian Federation, No. 95 of 04.02.2015
[9] ***, Federal Law of the Russian Federation No. 170-FZ of 21.11.1995, (in Russian)
[10] Kachan, P. P., *et al*., Experience of Exploiting the Radioactive Waste Recycling Complex at the Smolensk NPP, *Radioaktivnye Otkhody – Radioactive Waste, 1* (2018), 2, pp. 34-41
[11] Avezniyazov, S. R., Stahiv, M. R., Experience of Recycling the Liquid Radioactive Waste at the Kola NPP (in Russian), *Radioaktivnye Otkhody – Radioactive Waste, 4* (2018), 5, pp. 49-54
[12] Volkov, A. S., Nalivajko, E. M., Radioactive Waste Management at the Novovoronezh NPP II-1 (NPP-2006 Design) (in Russian), *Izvestiya Vuzov, Yadernaya Energetika – Nuclear Energy and Technology*, 3 (2017), Oct., pp. 183-194
[13] ***, Environmental Reports of JSC „Concern Rosenergoatom", URL: https://www.rosenergoatom.ru/safety_environment/vozdeystvie-na-okruzhayushchuyu-sredu/ekologicheskie-otchety-ao-kontsern-rosenergoatom/ (02.03.2020)
[14] Ekidin, A. A., Antonov, K. L., Application of a Specific Indicator for the Estimation of Radioactive Wastes Generation Volumes During Normal Operation of Nuclear Power Plants in Russia (in Russian), *Radioactive Waste, 2* (2020), 11, pp. 66-74
[15] ***, Power Reactor Information System (PRIS), IAEA, URL: https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=RU (25.08.2019)
[16] ***, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Waste Management, INPRO Manual, IAEA-TECDOC-1901, IAEA, Vienna, 2020
[17] Desyatov, D. D., Ekidin, A. A., Evaluation of Tritium's Entry Into the Environment from Nuclear Power Plants' Emissions (in Russian), Biosfer. Sovmest.: Chelovek, Region, *Tekhnol, 1* (2018), 21, pp. 88-96
[18] Nazarov, E. I., *et al*., Assessment of the Atmospheric Carbon-14 Caused by NPP Emissions (in Russian), *Izv. Vyssh. Uchebn. Zaved., Fiz. V. 61* (2018), 12-2 (732), pp. 67-73
[19] ***, Decree of the Government of the Russian Federation of 2 June 2014, no. 506-12 „On Approval of the State Program of the Russian Federation Development of the Nuclear Power Industry Complex" (in Russian)

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## СПЕЦИФИЦНА ЗАПРЕМИНА ОТПАДА ЗА РЕТРОСПЕКТИВНЕ, ПРЕДИКТИВНЕ ПРОЦЕНЕ И РАНГИРАЊЕ ПРАКСЕ ТОКОМ НОРМАЛНОГ РАДА РУСКИХ НУКЛЕАРНИХ ЕЛЕКТРАНА

Приказане су могућности примене специфичне запремине производње радиоактивног отпада по јединици произведене електричне енергије. Ова специфична запремина отпада користи се за ретроспективну процену и предвиђање количина радиоактивног отпада насталог у руским нуклеарним електранама. Према доступним подацима за период 2008–2021, добијене су средње вредности и медијане годишње специфичне запремине отпада за сваку нуклеарну електрану. Медијане за чврст радиоактивни отпад, који се дели на категорије веома ниског радиоактивног отпада, нискоактивног отпада, отпада средњег нивоа и високоактивног отпада, износиле су $3.6\cdot10^{-2}$, $3.2\cdot10^{-2}$, $3.2\cdot10^{-3}$ и $3.0\cdot10^{-4}$ $m^3(GWh)^{-1}$, респективно. За течни радиоактивни отпад, категорије нискоактивног отпада и средњеактивног отпада биле су $1.3\cdot10^{-3}$ и $2.4\cdot10^{-2}$, респективно. Највеће средње вредности и медијане специфичне запремине отпада за све категорије радиоактивног отпада типичне су за нуклеарне електране са LWGR (RBMK) реакторским инсталацијама. Прогноза заснована на плановима за повећање производње електричне енергије у руским нуклеарним електранама указује на вероватно повећање обима производње радиоактивног отпада за 0.7–7.4 % (у зависности од категорије отпада), у периоду од 2022. до 2027. године. Употреба специфичне запремине омогућава рангирање постојећих пракси рада нуклеарних електрана према количини насталог радиоактивног отпада како би се оправдали критеријуми за усаглашеност са методологијом одрживости према Међународном пројекту о иновативним нуклеарним реакторима

*Кључне речи: радиоактивни отпад, специфична запремина отпада, реакторско постројење, нуклеарна електрана, иновативни нуклеарни реактор*