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MULTI-PURPOSE PACKAGES FOR RADIOACTIVE WASTE

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A number of acts in the field of the radioactive waste (RW) management are adopted in the Russian Federation; they allow rethinking the solutions that are in use now and proposing new ones that are more economically efficient and take into account all basic costs of life cycle related to management of RW generated at enterprises operating radiation-hazardous productions. The in-force Russian regulatory framework allows proposing general technical and economic approaches to multi-purpose protective packages for storage, transportation and final isolation of radioactive waste. The analysis of technical and economic characteristics of RW packages given in the present article is based on a long-term experience of JSC Engineering Center of Nuclear Containers on development, manufacturing and application of the unified series of packing sets for transportation, storage and disposal of radioactive waste of various classes (specific activities).

Keywords: *NPP, HLW, acceptance criteria, multi-purpose casks, LLW, radioactive waste, ILW, disposal fee, RW specific activity.*

Introduction

A number of acts in the field of radioactive waste management were adopted in the Russian Federation in the period from 2011 to 2016 [1—4]. These acts allow revising the solutions currently used for RW management.

The most important of the requirements addressing the target condition of the established RW management system is the requirement to transfer all the generated RW to the National Operator for disposal, and their conditioning in accordance with waste acceptance criteria. This condition allows the development of systematic requirements to technological and economic parameters of multipurpose packages used for long-term storage, transportation and disposal of radioactive waste, since the radioactive waste disposal fee [5] is set per a unit of volume of the disposal facility and includes the payment for the volume of the package (cask) itself. Radioactive waste (RW) results from operation of nuclear industry facilities, in medical and industrial application of radionuclides, mining activities.

The largest contribution to the generation of radioactive waste makes the nuclear industry — starting from ore mining and enrichment to operation of nuclear fuel cycle facilities, nuclear power generation facilities, research centres, etc. The main type of radioactive waste generated at facilities that do not belong to the nuclear industry are sealed radioactive sources (SRS) with expired specified lifetime [6].

For example, the total annual volume of RW generated at NPP of JSC "Concern "Rosenergoatom" is approximately 10,000 m^3 [7]. HLW (2 class according to NP-093-014) comprises about 2.5% of the overall amount of waste generated, the rest is 3 and 4 class RW [8].

The overall amount of solid radioactive waste stored at Russian NPPs as of December 31, 2016, is over 190,0 thous. m^3 [6]. Description of morphology

Table 1. Morphology description of NFC RW flows [9–11]

RW flow (morphology)	RW class
Polymer products (polyethylene, rubber, etc.)	3, 4
Metal waste (ferrous and non-ferrous metals in equipment and elements)	2, 3, 4
Individual protection equipment (overalls, boots, paper, fabric, etc.)	3, 4
Used ion-exchange resins, pulps, slams, sludge	2, 3, 4
Mixed waste (construction debris, concrete, etc.).	3, 4
Graphite	2, 3
NFMC*, spent SRS	2, 3
Bottom residues (evaporated salt concentrate)	3, 4
Non-organic materials (glass, ceramics, heat insulation)	3, 4

*NNFMC — Neutron Flux Measurement Channel.

of the main types of RW generated in operation of nuclear fuel cycle (NFC) facilities is given in Table 1.

The main technologies of RW conditioning for subsequent disposal are compacting (pressing incineration, deep evaporation, etc.), drying and immobilization (cementation, vitrification, etc.). The final stage of conditioning is placement of prepared RW into radiation-shielded packages (casks) suitable for storage and/or transportation and subsequent disposal at final isolation facilities.

This paper presents the analysis of operator costs for RW management aimed at identifying possibilities of cost reduction in using various types of packages (casks) for RW management until disposal stage.

Basic requirements to multi-purpose packages

The in-force regulatory framework for RW management in the Russian Federation provides reliable and safe collection, processing, conditioning, transportation, storage, and disposal of radioactive waste. In accordance with NP-093-14, the retrievable RW is divided into classes (Table 2).

Boundary conditions for applicability of radioactive waste casks are requirements on conformance of dimensions, weight and construction solutions of the packages to the existing transportation flow charts of RW management at nuclear facilities, and compliance of the packages to the regulatory requirements specifying package design, contents, service life, etc. The basic regulatory documents include NRB-99/2009 "Radiation Safety Standards", NP-053-16 "Safety Rules for Transportation of Radioactive Materials", SanPiN 2.6.1.1281-03 "Sanitary Rules for Radiation Safety of Personnel and Population during Transportation of Radioactive Materials" and NP-093-14 "Criteria for Acceptance of Radioactive Waste for Disposal". Regulatory documents and boundary conditions regulating radiation shielding characteristics of RW packages are given in Fig. 1.

The annual effective dose limits for the personnel of nuclear facilities engaged in collection, conditioning and storage of RW set by NRB-99/2009 may impose additional requirements on RW packages.

Packages for RW management shall have certificates for the package design issued in accordance with the Law "On Technical Regulation" [14] and/or (in the interim period) a certificate of conformance within the "System of Certification of Equipment, Components and Technologies" [15].

Four transport categories of radiation protection containers are distinguished for transportation purposes [16]. Each of the categories has specific limits of equivalent dose rate on the surface of the package and at 1 m distance, as well as at the surface of a vehicle and at 2 meters' from its surface, assigned by the requirements of SanPiN 2.6.1.1281-03. The packages for RW transportation shall have certificates (permits) for package design issued by State Competent Authority (SCA) for nuclear and radiation safety in transport of nuclear and radioactive materials, and products of these materials,

Table 2. Categorization of solid radioactive waste [12]

Class	Category [12]	Specific activity, Bq/g	Management features
2	HLW	$> 10^7$ (beta-emitting) $> 10^6$ (alpha-emitting)	to be disposed of in deep disposal facilities for radioactive waste without preliminary storage to reduce heat output
	ILW	containing radionuclides with half-life of over 31 years $10^4 \ldots 10^7$ (beta-emitting) $10^3 \ldots 10^6$ (alpha-emitting)	
3	ILW	$10^4 \ldots 10^7$ (beta-emitting) $10^3 \ldots 10^6$ (alpha-emitting)	to be disposed of in near-surface disposal facilities for radioactive waste at the depth of up to 100 meters
	LLW	containing radionuclides with half-life of over 31 years $10^3 \ldots 10^4$ (beta-emitting) $10^2 \ldots 10^3$ (alpha-emitting)	
4	LLW	$10^3 \ldots 10^4$ (beta-emitting) $10^2 \ldots 10^3$ (alpha-emitting)	to be disposed of in near-surface disposal facilities for radioactive waste at the surface level
	VLLW	до 10^3 (beta-emitting) до 10^2 (alpha-emitting)	

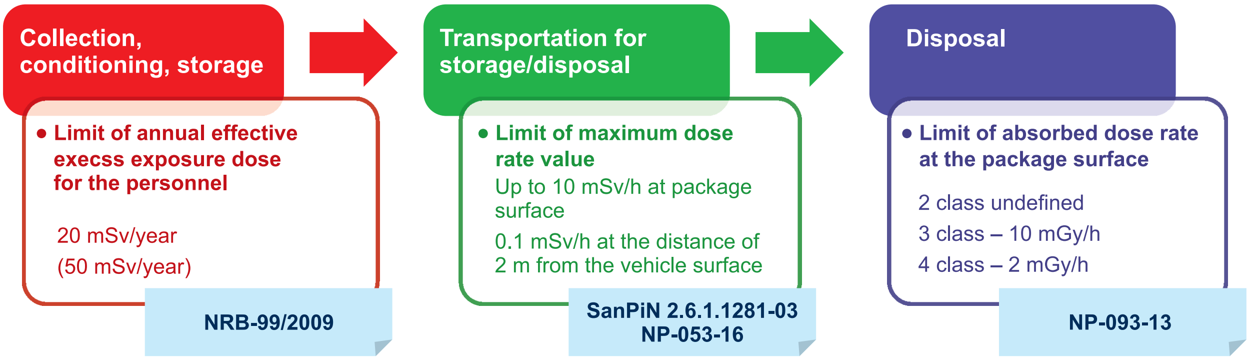

Fig. 1. Regulatory documents and boundary conditions regulating the criterion of equivalent dose rates from RW package

and certificates (permits) for transportation of the packagespecifying, if necessary, the vehicle and route of the transportation. The functions of SCA in the Russian Federation are assigned to the State Corporation "Rosatom".

The requirements to the packages placed at the disposal facility are regulated by provisions of NP-093-14, which limit the absorbed dose rate at the surface of the package. Packages for RW to be placed at the disposal facility shall have certificates of conformance for the package design issued in accordance with the Law "On Technical Regulation" [14] and/or (in the interim period) certificate of conformance within the "System of Certification of Equipment, Components and Technologies" [15].

Russian and foreign RW packages

A wide range of packages is currently used for management of radioactive waste generated by radiation-hazardous facilities.

The concrete packages (type NZK III, NZK-150-1.5P and their modifications) for RW of 2, 3, and 4 classes and thin-wall metal packages (type KMZ, KRAD, KM RAO etc.) for 4 class RW (Fig. 2) are used most frequently. JSC "Engineering Center of Nuclear Containers with the authors of this paper developed a wide range of standardized RW casks with bodies of ductile cast iron (see example in Fig. 2). The present analysis includes the above-mentioned packages with external dimensions corresponding to the dimensions of NZK-150-1.5P (KMZ) type containers with cask wall thickness from 50 to 150 mm, abbreviated below as ZUM (shielded metal package).

Similar cask designs of concrete and thin-walled metal are used for storage, predominantly of low-level waste, abroad. Multi-purpose thick-walled metal casks (for HLW and ILW), sandwich (with various fillings of body walls) and light (for LLW and VLLW) flexible packages are also widely used. Some of the design solutions are illustrated in Fig. 3.

Multi-purpose (intermediate storage, transportation and disposal of RW) casks of ductile cast iron are produced by the German company Siempelkamp. Casks of fiber-concrete are produced by another major RW cask supplier — Sogefibre company, a part of Areva group of companies. Flexible packages made of high strength geotextiles are produced by the American company PacTec.

Assessment of required radiation shielding thickness for various RW classes

The main functions of a container are isolation (containment) of the contents and protection of the environment and personnel from radiation both in regular operations and in emergencies. Calculations of the effective dose rate (in accordance with NRB-99/2009) beyond the protection barrier rated to specific activity of the radioactive contents of the uniformly filled cask were carried out to determine the required thickness of the package walls. A one-dimension problem of gamma-radiation penetration through a protection barrier with an absorbing half-infinite source was solved (conservative calculations). Silicon dioxide with uniform distribution of radionuclides (^{60}Co and ^{137}Cs in various ratios) was selected as a source material, having relatively small capability to absorb gamma-radiation and can be included in RW in considerable quantities as a part of cement compound (conservative calculations).

Fig. 4 shows the calculated values of the required thickness for the shieling of concrete with densities of 4.2 and 2.2 g/cm^3 (similar to NZK-III and NZK-150-15P casks) and of ductile cast iron (ρ = 7.2 g/cm^3) required to meet the limit of dose rate at the package surface of 10 mSv/h depending on the value of specific activity of the simulated RW in the filled package. The dose rate limit is set for conditions of transportation under exclusive use in accordance with the paragraph 3.4 of SanPiN 2.6.1281-03 "Sanitary Rules for Radiation Safety of Personnel and Population during Transportation of Radioactive Materials (Subst)". The same limit is defined for location of 3 class RW at disposal facilities in accordance with NP-093-14.

Figure 4 shows that metal packages having higher absorbing capabilities than concrete are

Fig. 2. NZK-150-1, 5P, KMZ and AK RI casks

Fig. 3. Foreign RW packages

capable of holding the same (in terms of specific activity) contents with considerably thinner walls of the cask body.

As for RW of 3 class, Fig. 4 demonstrates that thick-walled metal casks are capable to hold comparable amounts of radioactive waste in much thinner body walls than concrete casks, e.g., a normal concrete cask (ρ = 2.2 g/cm^3) required for waste with specific activity of 1.6E+06 Bq/g with no ^{60}Co shall have 150 mm thick wall, while cast iron cask requires only 50 mm.

See Fig. 5 for thickness variation for the shielding of normal concrete (ρ = 2.2 g/cm^3) or metal (steel, ρ = 7.8 g/cm^3) depending on the value of specific activity (conservatively only for ^{60}Co) for class 3 and class 4 waste to be placed in the package assuring limited dose rate at the surface of the package of up to 2 mSv/h.

The dose rate limit value is defined by the package acceptance criteria for 4 class RW in accordance with NP-093-14 "Criteria for Acceptance of Radioactive Waste for Disposal" and for transportation by general transport in accordance with the paragraph 3.4 of SanPiN 2.6.1281-03 "Sanitary Rules for Radiation Safety of Personnel and Population during Transportation of Radioactive Materials". The dose rate limit is typical for completed projects of some storage and disposal facilities for 3 and 4 class radioactive waste, and for RW transportation on a regular basis.

Fig. 5 confirms all conclusions previously made when analyzing Fig. 4 for 3 class intermediate level waste Besides, Fig. 5 leads to an important conclusion: 4 class low-level waste (specific activity of radioactive contents under 10^4 Bq/g) require no additional radiation shielding — the package serves as an isolation barrier and provides easy handling of waste.

Feasibility study of package use

In the general case, the costs of RW management [1], [18] include the costs of bringing RW into conformance with the acceptance criteria, including costs for RW packages, intermediate storage and transportation of casks to the site of acceptance by the national operator, and, finally, disposal fee per gross volume of packages with RW [2].

The disposal fees for RW of different classes [5] are defined per a unit of RW volume brought in compliance with acceptance criteria for each category of RW, including the package volume, and cannot be optimized. Optimization of lifecycle costs is possible with respect to waste compacting, the cost of packages used and the number required.

The Economic efficiency of various packages used for storage of the required RW volume, in general, depends on package capacity utilization factor, which is calculated as a ratio of disposed RW volume to the external volume of the package itself. Thus, for the currently used Russian NZK-III cask this parameter equals to 0.16, for widely used NZK-150-1.5P cask it is at the level of 0.4. Volume utilization factor for thin-walled metal KRAD, KMZ type packages is higher and may exceed 0.8.

As demonstrated above, an increase in volume utilization factor of the package by maintaining its radiation shielding properties can be provided by

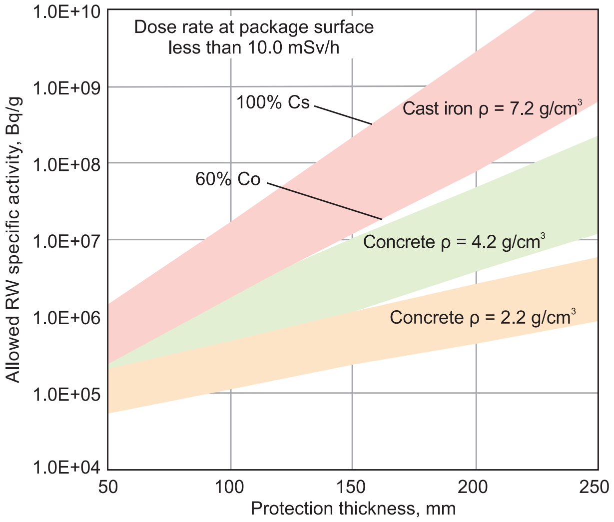

Fig. 4. Determination of thickness of radiation shielded cask body for storage of 2 and 3 class waste

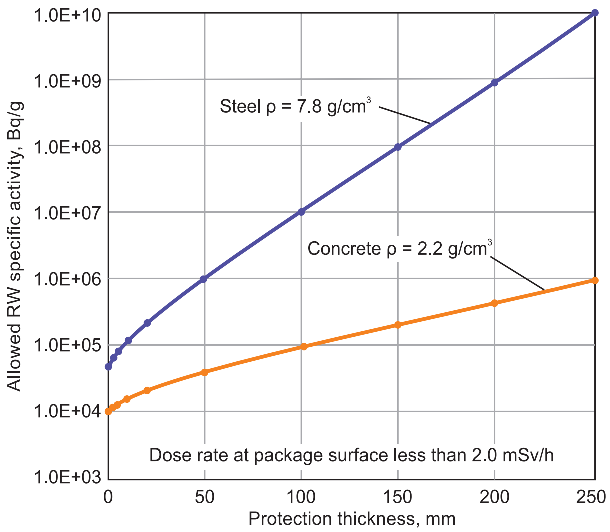

Fig. 5. Determination of thickness of radiation shielded cask body for storage of 3 and 4 class waste

reduction of the required wall thickness of the cask, thus increasing the product volume utilization factor. This requires a structural material with higher radiation shielding properties compared to the currently used concrete grades.

Table 3 gives basic technical and economic parameters of the standardized range of ZUM casks (shielded metal package) and the currently used RW casks.

Table 3 shows that the inner cavity of the ductile cast iron cask having the same external dimensions shall be greater. Consequently, location of the same RW volume requires significantly fewer casks, smaller storage areas and fewer shipments to the final disposal facility of RW.

The feasibility study given below has been performed for the integral parameter — cost of disposal of 1 m^3 of RW of a certain class in a certain package, including total costs of 'disposal' and costs of packages for disposal. Sensitivity of costs to changes of RW disposal fees and costs of packages has been analyzed for 2, 3 and 4 class RW packages.

A potential increase of RW disposal fees was considered based on the fact that the cost of RW disposal in Russia is currently lower than similar fees in other countries [19]. This is due to the fact that the Russian fees in the initial period take into account short-term regulation parameters. Subsequently, the long-term regulation methods shall apply, and in the long run, the cost of RW disposal in the Russian Federation may reach the international level, since the fees calculated considering long-term regulation parameters may include costs of construction of disposal facilities for corresponding classes of radioactive waste stipulated by the production and/or investment programs of the National operator [2].

Potential change in the packages cost was considered mainly based on a possibility to organize mass production of products, resulting in price reduction compared to small-batch or piece production.

It should be noted that payments for future RW disposal are made by operators as the waste

Table 3. Technical and economic parameters for RW packages

Description	Material	Capacity utilization factor	Cost, thous. roub.
NZK-III	concrete ρ = 4.2 g/sm³	0.16	700.0
NZK-150-1.5P	concrete ρ = 2.2 g/sm³	0.40	120.0
ZUM 150	cast iron ρ = 7.2 g/sm³	0.45	3,500.0
ZUM 120	cast iron ρ = 7.2 g/sm³	0.60	2,200.0
ZUM 70	cast iron ρ = 7.2 g/sm³	0.70	800.0
ZUM 50	cast iron ρ = 7.2 g/sm³	0.80	700.0
KRAD 3	sheet steel	0.75	120.0
KMZ	sheet steel	0.8	150.0
Flexible package	geotextile	0.9	60.0

Fig. 6. Structure of disposal cost for 2 and 3 class RW

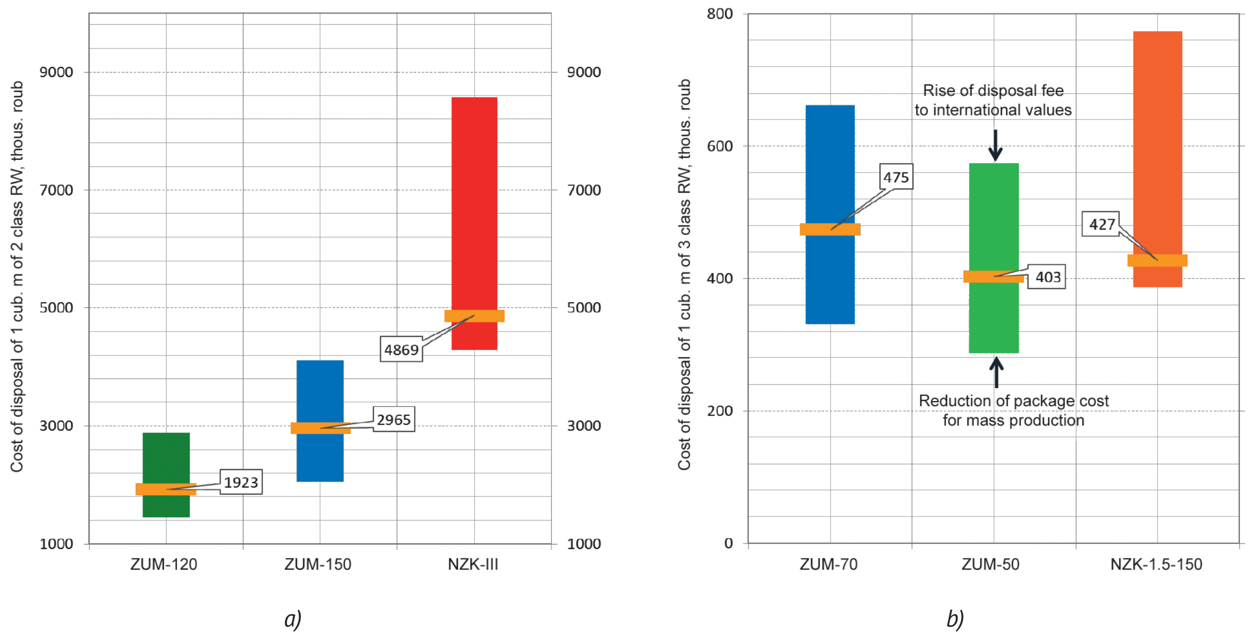

Fig. 7.Analysis of variation of disposal cost based on the level of disposal fees and reduction of package costs: a — 2 class RW; b — 3 class RW

generates, i.e. annually. Payment for the packages is made by companies as RW is being prepared for disposal within 10 years. The time limit of intermediate storage of removable radioactive waste generated after the Federal Law of 11.07.2012 No. 190-FZ became effective has been defined for organizations operating especially radiation-hazardous and nuclear-hazardous facilities and assuming ownership of radioactive waste, including the right of economic authority and operating management by the state authority in the field of RW management – State Corporation Rosatom [20]. During the intermediate storage period RW shall be prepared for transfer to the National operator. It means that for a long time the cost of packages remains under the operator's control and may be subject to application of financial tools during the period of intermediate storage to reduce conditioning costs.

The general analysis of the cost structure required for RW disposal (Fig. 6) shows that disposal fees dominate in the cost structure, when using concrete casks, whereas for metal casks the situation is reverse: manufacturing of packages represents the major part of costs. Analysis of disposal cost variation depending on increase of the fee (Fig. 7) shows that concrete casks are very sensitive

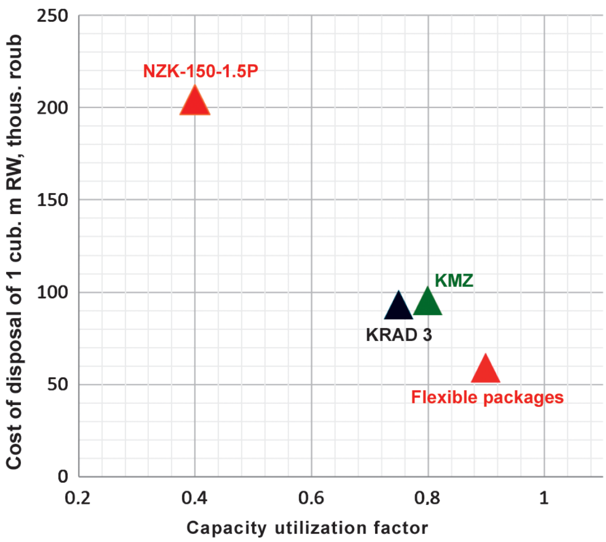

Fig. 8. Comparison of costs for disposal of 4 class RW

to an increase in disposal fee, defining outrunning growth of RW disposal in concrete casks compared to the cost growth of disposal in metal casks.

Metal casks are less sensitive to the growth of the disposal fee.

Analysis of disposal cost variation in case of package cost reduction (Fig. 7) shows that reduction of the cask cost for 2 class RW does not substantially affect the feasibility parameters of package use. As for the concrete casks for 3 class RW, the sensitivity of disposal costs to the package cost is also low. At the same time, for metal casks for 3 class RW, there is a significant potential for disposal costs reduction in case of reduction of the package manufacturing cost, i.e. organization of mass production gives significant improvement of the technical and economic parameters of the metal cask use.

Comparison of costs for disposal of 1 m^3 of 4 class RW for concrete, metal and flexible packages is given in Fig. 8.

The comparison shows that the cost for disposal of 1 m^3 of 4 class RW in concrete package NZK-150-1.5P is considerably higher than for the similar metal casks. In spite of the current practice, the use of NZK-150-1.5P for 4 class RW is extremely inefficient.

It should be noted that the majority of radioactive waste generated at nuclear facilities is 4 class RW. This leads to the conclusion that a reduction in costs for disposal of each cubic meter of 4 class radioactive waste leads to a considerable reduction in the total scope of deferred obligations of operators.

Conclusions

A number of acts in the field of radioactive waste management aimed at optimization of RW classification, regulating the issue of documents for RW disposal and standardization of technological requirements to packages for radioactive waste storage and final disposal were adopted between 2011 and 2016. The in-force Russian regulatory framework allows revising the currently applied conservative and costly solutions in RW management providing systematic solutions that are more effective.

The feasibility study using an integral parameter has demonstrated that there is a high sensitivity to the growth of RW disposal fee in case of use of concrete casks, while an impact of package cost reduction on the overall disposal cost is low. At the same time, for metal packages, there is higher cost stability in case of disposal fee increase and there is a considerable potential to reduce disposal cost, if individual package cost is reduced. Therefore, it is reasonable to use metal casks of NZK geometry for 2 and 3 class RW.

For radioactive waste of 4 class with specific activity below 1.0E+04 Bq/g the use of NZK concrete casks is inefficient. It is advisable to consider flexible packages with better technical and economic parameters compared to thin-walled metal casks for 4 class RW.

Optimization of technical solutions on the use of packages allows forecasting the lifecycle costs for RW management. The right choice of RW packages also gives a substantial reduction in estimated obligations on radioactive waste management.

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