SCIENTIFIC AND DESIGN ASPECTS IN THE DEVELOPMENT OF NEAR-SURFACE DISPOSAL FACILITIES FOR LOW- AND INTERMEDIATE-LEVEL WASTE

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The article presents various design options for the development of near-surface radioactive waste disposal facilities and materials constituting to the engineered safety barriers. It considers the cost ratios associated with the establishment of engineered safety barrier systems. The paper presents some proposals regarding the decision-making on particular types and designs of near-surface radioactive waste disposal facilities aimed at increasing the safety and reducing the RW disposal costs.

Keywords: *radioactive waste, near-surface radioactive waste disposal facilities, engineered safety barriers, radioactive waste disposal containers, the cost of radioactive waste disposal, buffer materials, radioactive waste disposal compartments.*

Introduction

In 2016, at the site of JSC Urals Electrochemical Combine, commissioned was the first RWDF for RW Class 3 and 4 in the Russian Federation [1] (their classification is indicated in accordance with [2]). In 2018, FSUE NO RAO received siting and construction permits for Class 3 and 4 RW disposal facilities at FSUE PA Mayak and JSC SCC sites [3, 4].

Similar-type disposal structures are used to accomodate the waste at these sites - shallow reinforced concrete structures (compartments) fitted with underlying and covering screens.

Successful state examination of design documentation and the possibility of obtaining relevant licenses for these facilities can be viewed as a prerequisite for replicating such structures in the Russian Federation. However, in some cases, the use of shallow RWDFs as a standard option appears to be infeasible and requires additional scientific, engineering and economic studies taking into account the parameters of the RWDF site, as well as the characteristics and volumes of RW subject to disposal. This article briefly analyses the RWDF types operated and designed in the Russian Federation and abroad summarizing their advantages and disadvantages with relevant recommendations provided on the decision-making regarding the RWDF types and designs that can be used in the design development process.

Brief analysis of operated and developed near-surface disposal facilities for RW

Federal Law No. 190 of July 11, 2011 establishes some fundamental principles for the classification of removable RW and the requirements for the selection of an appropriate repository type [2]. Decree of the Government of the Russian Federation of October 19, 2012 No. 1069 [5] elaborates on these requirements and establishes numerical classification criteria. In accordance with these regulations, conditioned solid low- and intermediate-level short-lived RW can be disposed of in near-surface disposal facilities.

At the same time, IAEA recommendations, namely, GSG-1 Classification of Radioactive Waste [6] present a different approach, according to which one or another class includes those RW that can be safely disposed of in a particular type of a repository.

Currently, amendments to be introduced to the RW classification criteria and the exclusion of the numerical indicators representing their characteristics defined in NP-093-14 [7] are being discussed, therefore, only partial criteria are going to be available in the design documentation developed for RW disposal facilities.

In this regard, enhancement of disposal designs considering various types of disposal facilities and the accumulated national and international experience is believed to be a topical task that should be addressed to identify most feasible disposal options for RW with different characteristics.

Considering global and national experience, repositories for low- and intermediate-level waste involve various types of surface, shallow and underground near-surface disposal structures.

At present time, Russian regulatory framework provides no specific requirements for EBS structures and materials. General design and safety requirements for disposal facilities are given in NP-055-14 [8] and NP-069-14 [9]. In accordance with these regulations, disposal facilities shall be fitted with systems of safety barriers (engineered and natural) preventing the spread of ionizing radiation and radioactive substances into the environment.

According to [9], EBS of a near-surface disposal facility involves:

- RW packaging and its individual elements (RW form, container);
- building structures of a near-surface disposal facility and their individual parts;
- structural materials of a RW disposal cell (in this article referred to as disposal compartment);
- buffer materials;
- underlying screen;
- overlying screen.

At the same time, these regulations provide no requirements stating that the above EBS list is necessary and/or sufficient for each near-surface disposal facility although this principle is implemented in some final disposal practices abroad, according to which the waste is disposed of in several structures of various designs.

For example, in France, the least hazardous waste category, but nevertheless accounting for the largest RW inventory according to its volume, namely, very low-level radioactive waste is disposed of in repositories of a simplified design located at the ground level fitted with a minimum number of engineered safety barriers, whereas low- and intermediate-level short-lived waste is disposed of in repositories located at the ground level and fitted with additional engineered barriers — reinforced concrete compartments. Underground RWDF located at a depth of several tens of meters is envisaged for long-lived low-level waste disposal. It is worth noting that in accordance with national RWDF designs [1, 3, 4], all these RW are planned to be disposed of in the same type of disposal facilities.

According to the regulatory framework of the Russian Federation (section II p. 24 [8] and p. 11 [9]), the purpose and properties of the safety barrier system are specified in the design documentation with relevant reasoning provided in the safety analysis report for the RW disposal facility.

Classification of repository systems and elements and requirements for their seismic resistance are established during design development in accordance with the regulatory provisions for nuclear power plants and nuclear fuel cycle enterprises — NP-016-05 and NP-031-01 [10, 11] (task-specific regulations establishing the classification and categorization of systems and elements specifically for near-surface disposal facilities have yet not been developed).

Structural elements of near-surface disposal facilities and EBS are designed according to this classification system, as well as taking into account the requirements of key radiation safety regulations OSPORB-99/2010 [12] and NRB-99-2009 [13]. Based on the results of the decisions made, the long-term disposal safety is assessed in accordance with RB-117-16 and NP-100-17 requirements [14, 15].

To establish the EBS classification system and EBS requirements for the design development stage, latest scientific and engineering advancements in EBS development and reference solutions implemented under existing near-surface disposal designs should be accounted for along with the requirements of regulatory and engineering documentation. Based on these, for example, selected are the buffer materials, specified is the layout (type) of near-surface disposal facilities, the designs of underlying and covering screens.

Considered below are some features of various near-surface disposal facility types.

Shallow near-surface disposal facilities

In case of shallow repositories, waste disposal compartments are located at a depth of several meters from the ground surface.

This type of near-surface disposal facilities is typical for dry climate regions and are developed in case of favorable hydrogeological site conditions with low groundwater levels.

Shallow repository designs are considered feasible if the underlying rocks are characterized by low or, conversely, high water permeability and the soil excavated during their construction can be used to backfill the disposal compartments and/or to install a covering screen. This mainly concerns sites located in areas with clay soils characterized by good insulating properties (Hungary (RWTDF) [16], Great Britain (Drigg) [17]) or highly permeable sands in arid regions (USA, Hanford [18], South Africa, Vaalputs [19]).

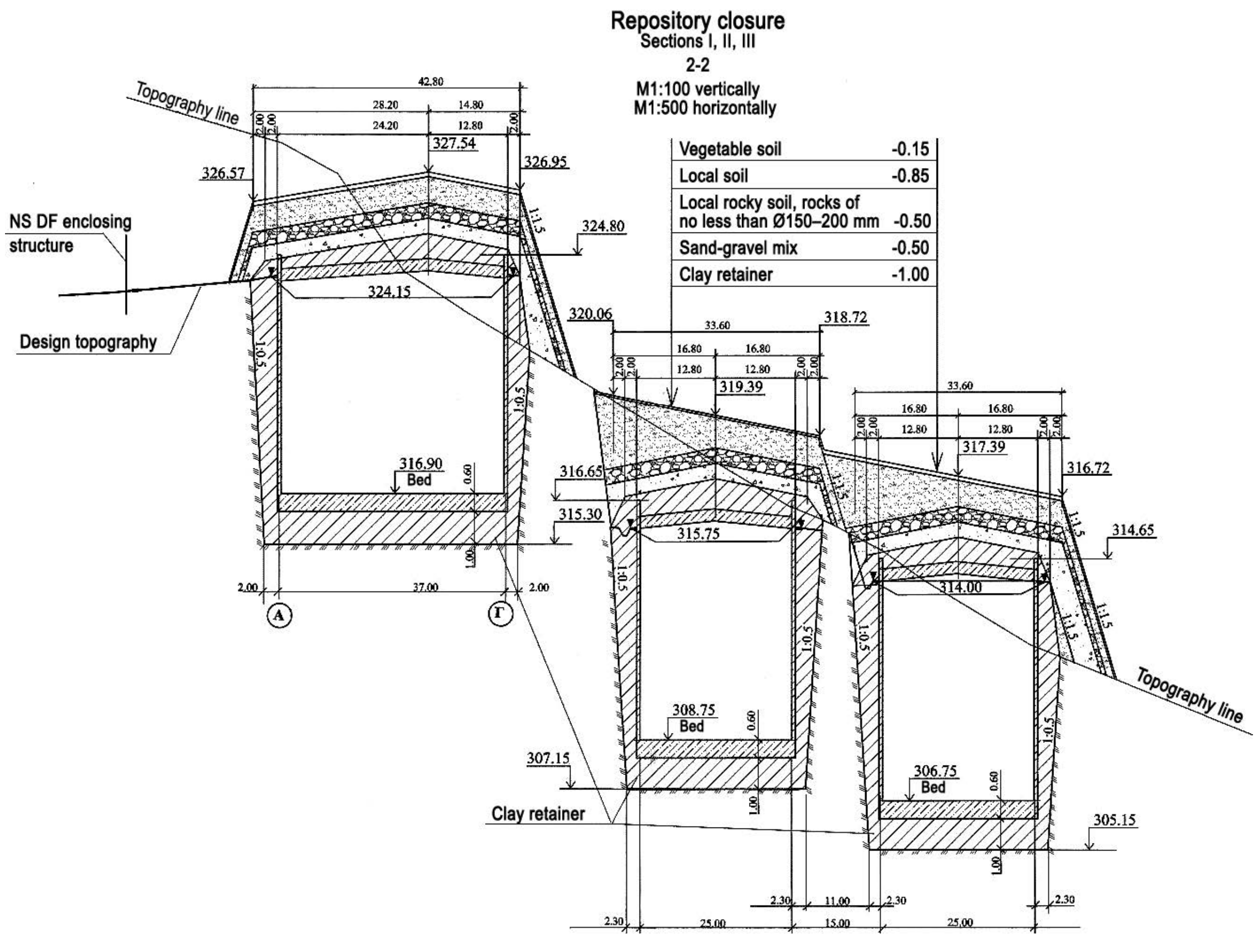

Figure 1. RWDF designs developed for the JSC UEIP site (containers and buffer material are not shown) [1]

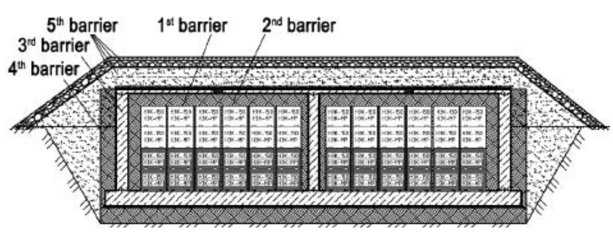

Figure 2. Near-surface disposal facility design developed for the sites of FSUE PA Mayak and JSC SCC [4]

1st barrier – container walls;
2nd barrier – buffer material (clay powder grade SBMK for the SCC site, bentonite granules for PA Mayak site);
3rd barrier – enclosing structures – disposal compartments (concrete structures of walls and ceilings of modular disposal structures);
4th barrier – clay retainer around the perimeter of modular structures;
5th barrier – covering waterproofing screen.

Shallow repository type was adopted as a standard one for the first Russian RW disposal facilities intended for RW Class 3 and 4 disposal. Figures 1 and 2 present the disposal designs developed for JSC UEIP, FSUE PA Mayak and JSC SCC sites.

The following engineering solutions are typical for these disposal structures:

- the lower part of the disposal compartments is sunk relative to the ground surface;

- RW of different classes are disposed of in the same compartments (class 4 RW packages are placed above class 3 RW packages);
- several safety barriers preventing radionuclide migration are applied;
- different types of packages are accepted for disposal.

To date, no adequate scientific and technical evidence support the application of the above engineering solutions at all disposal sites with no account taken of their specific features suggesting opportunities for de integro consideration of these designs.

Above-ground near-surface disposal facilities

Operation of first shallow repositories [20] has shown that they are prone to flooding due to natural or man-induced rise of the groundwater level, which contradicts the most important safety requirement established for RW disposal facilities stating that no water should be available within the disposal zone.

Above-ground repositories are located at the ground level, which significantly reduces the risks of groundwater ingress into the RW disposal area. Therefore, it seems sufficient that the seepage of precipitation through the upper covering screen and capillary rise of groundwater through the lower underlying screen is limited by available engineering solutions.

For these reasons, France switched from the trench disposal option previously used for low- and intermediate-level short-lived RW to above-ground disposal option [20] (see Figure 3).

The same decisions are followed in a number of other countries, including Belgium, Spain, Lithuania [21].

The set of engineered barriers applied both in above-ground and shallow disposal facilities is more or less the same, whereas the underlying screen designs developed for the above-ground repositories is simpler than in case of shallow ones.

Special focus should be placed on addressing the challenge of maintaining the insulating capacity of the covering screen, which is relevant both for above-ground and shallow RW disposal facilities. To prevent degradation and subsidence of covering screens, their regular monitoring and maintenance is required, as well as the development of appropriate engineering solutions minimizing the voids available within the RW container arrays, restraining the growth of shrubs and trees that can potentially destroy the upper layers of the screen by their root systems, obstructing the denudation processes. The above issues are missing in case of underground RWDF.

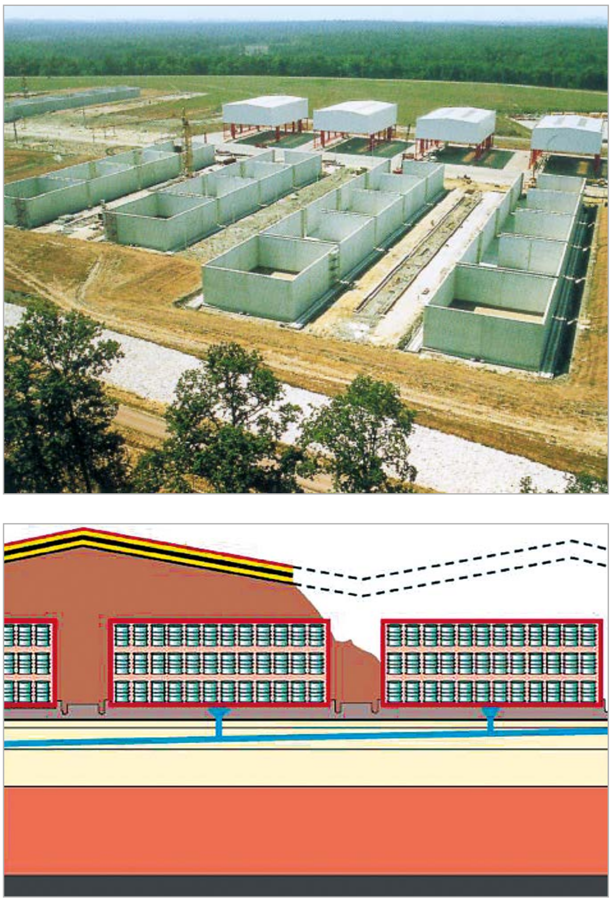

Figure 3. Above-ground RWDF for short-lived LLW and ILW in France (above – photo of empty compartments for radioactive waste disposal, below – layout of a multilayer covering screen installed above the compartments filled with waste)

Underground near-surface disposal facilities

Underground (buried) RWDF are located at a depth of several tens of meters. They are resistant to external influences and are most reliable when sited in appropriate hydrogeological conditions.

In comparison with above-ground and shallow repositories, this type of near-surface disposal facilities provides favorable nature of water flows after their interaction with the waste: water does not enter the surface runoff, but is released into aquifers, which significantly reduces the rate of radionuclide migration.

For these reasons, a big number of European countries operating nuclear power plants already operate or plan to develop underground near-surface disposal facilities for low- and intermediate-level waste (Germany, Sweden, Finland, Slovenia, Hungary, Switzerland [21]).

The use of underground RWDF also partially addresses the disposal problem considered typical for RW containing long-lived radionuclides. The long-term safety demonstration experience of JSC UEIP, FSUE PA Mayak and JSC SCC indicates that the content of long-lived radionuclides in them meeting the categorization criteria for RW Class 3 according to the classification system adopted in Russia [5] should be limited additionally not to exceed the dose limits for the population established in the radiation safety standards [13].

In this case, disposal of such waste as, for example, reactor graphite from the decommissioning of nuclear power plants with RBMK reactor units that can be categorized as RW Class 3 in above-ground or shallow disposal facilities is impossible due to the high content of the long-lived ^{14}C.

It was previously proposed to dispose of RW Class 3 containing long-lived radionuclides and not meeting local RWDF acceptance criteria in empty excavations of a deep disposal facility [23]. However, taking into account the schedule for the development of a deep disposal facility in Russia [24], disposal of such RW may be postponed for more than 40 years. Therefore, some comprehensive solution addressing the disposal challenge for RW Class 3 containing long-lived radionuclides may provide for the development of a separate regional underground (shallow) RWDFs. Figure 4 presents some examples of such repositories for low- and intermediate-level waste containing long-lived radionuclides developed for the North-Western Territorial District of the Russian Federation.

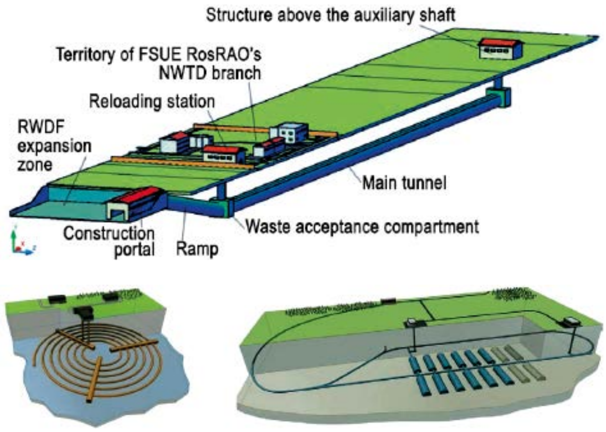

Figure 4. Examples of shallow designs for near-surface disposal facilities developed for the North-Western Territorial District of the Russian Federation: from above — a tunnel structure excavated using a tunnelling machine, at the bottom left — a spiral structure, at the bottom right — a chamber structure [25]

Comparison of different repository types

Table 1 compares various types of near-surface disposal facilities taking into account the inherent advantages and disadvantages of these types.

Feasibility study of near-surface disposal facilities for RW

According to [26], for above-ground and shallow disposal facilities, specific capital disposal costs per 1 m^3 of disposed RW are more or less the same. Specific capital underground disposal costs per 1 m^3 of RW are on average 30 % higher than those common for the former ones assuming comparable operating costs. This is due to additional costs for excavation and surface infrastructure supporting the operation of the underground section (mine structures, ventilation systems of underground excavations, etc.).

Table 1. Advantages and disadvantages of near-surface disposal designs

Advantages	Disadvantages
Above-ground	
• Low capital costs for construction • Less stringent requirements for site geology • Simpler loading flowchart in terms of package transportation and handling	• Impact of seasonal temperature fluctuations • Large areas of expropriated territory • Sophisticated multi-layer covering screen • Covering screen requiring maintenance • Sensitivity to external influences (especially at the package loading phase)
Shallow	
• Low capital costs for construction • Simpler loading flowchart in terms of package transportation and handling • Smaller size of the covering screen compared to above-ground repositories	Same disadvantages as in case of the above-ground option, plus • additional excavation is required; • possible flooding due to groundwater level fluctuations
Underground	
• Resistance to external influences • No seasonal temperature fluctuations • Presence of a geological safety barrier • Small areas of expropriated territory (surface part of the RWDF) • Opportunities for the disposal of most dangerous RW Class 3 containing long-lived and weakly absorbed radionuclides (due to the presence of a geological safety barrier)	• High capital costs for construction • Special requirements for site geology • Special requirements for RW handling equipment

However, in case of underground disposal, costs can be reduced due to shorter monitoring period, more rational use of surface areas and no need for the installation of covering screens and their maintenance, which is required in case of above-ground and shallow RWDFs.

Considering all repository types, RW disposal costs can be reduced by optimizing the entire EBS system, including RW containers and waste form. Based on the analyzed design and estimate documentation developed for a near-surface repository in the Ozersk city, as well as a number of other sources, [27] provides the disposal cost decomposition considering each barrier. Table 2 shows cost distribution for each EBS. At the same time, the cost of the entire EBS set was taken into account, including the waste form and RW containers, the costs of which are borne by RW generators.

Table 2. Breakdown of costs for EBS supply/ construction/installation

<table>
<tr><th>EBS</th><th colspan="2">Percentage of the sum involving all costs for EBS supply / construction / installation</th><th>Note</th></tr>
<tr><td>Waste form (RW matrix)</td><td>5–15</td><td rowspan="6">100 %</td><td>Waste supplier cost</td></tr>
<tr><td>Container (NZK, KMZ, KRAD)</td><td>40–60</td><td></td></tr>
<tr><td>Buffer</td><td>3–10</td><td>FSUE NO RAO cost</td></tr>
<tr><td>Enclosing structures (disposal compartments)</td><td>15–25</td><td></td></tr>
<tr><td>Underlying screen</td><td>3–5</td><td></td></tr>
<tr><td>Covering screen</td><td>10–15</td><td></td></tr>
<tr><td>Geological barrier</td><td colspan="2">–</td><td>–</td></tr>
</table>

Table 2 demonstrates that containers and enclosing structures, i.e., disposal compartments have the largest contribution to the cost of the entire EBS system.

In this regard, to optimize the cost of near-surface repository construction, opportunities providing the reduction of costs associated with RW disposal containers and the construction of disposal compartments may be considered.

Selection of RW disposal containers

In the RW management system, containers are of great importance. They can serve as primary containers to form radiation packaging, meet the requirements for long-term storage, RW transportation and act as a safety barrier in the safety system of a near-surface disposal facility.

Under near-surface disposal designs implemented at JSC UEIP, FSUE PA Mayak and JSC SCC sites, various types of containers are used for RW disposal with some of these presented in Table 3.

Table 3. Some characteristics of RW disposal containers

Name of container	Material	Barrier thickness, mm	Insulation capacity	Period of insulation capacity retention
NZK container	reinforced concrete	100–150	Air leakage – no more than 500 Pa/l·s^{-1} [27]	more than 300 years [28]
KMZ container	Steel	5	No data available	No data available
KRAD container	Steel	4	No data available	No data available
Put up 200 l drums	Steel	0.6–1.8	untightened	–

A decision regarding particular RW disposal container designs is made with an account taken of the waste characteristics, the design features of the disposal facility, regulatory requirements, in particular those set forth in NP-093-14 [7].

Certified protective non-returnable reinforced concrete container of NZK type is the only type of containers that can be used for RW Class 3 disposal purposes: its insulating capacity retention period of 300 years has been demonstrated and it fully meets NP-093-14 requirements [28].

The use of metal KRAD- and KMZ-type containers for the disposal of RW Class 3 and 4 as non-recoverable ones has some important advantages over the reinforced concrete ones in terms of their capacity. However, to date, its feasibility has not been yet demonstrated due to the following:
- their cost is comparable to the one of NZK containers and is considered too high for RW Class 4 disposal;
- no evidence suggests that their insulating capacity can be retained for 100 years in accordance with the requirements of NP-093-14 for RW Class 3 packages.

The use of KRAD and KMZ-type containers as safety barriers should be considered with an account taken of all protective barriers of the disposal system as a whole.

NP-093-14 provides a minimum set of requirements for RW Class 4 packages:
- restricted activity of radionuclides in the package;
- restricted absorbed dose rate on the package surface (no more than 2 mGy/h);
- restricted permissible level of non-fixed surface contamination;

- the ability of the package to retain its insulating function until it is emplaced into the disposal facility.

The above requirements are met by various general industrial packaging including 200 l drums according to GOST 13950-91 [29]. However, in case of off-site waste transportation, the packages should comply with the NP-053-16 requirements [30]. Therefore, for LLW transportation and disposal purposes, expensive purpose-designed RW containers with all necessary certificates are used along with economical general-purpose industrial packages.

To address these problems, simultaneously with the use of revolving RW shipment containers, it is advisable to consider the use of economical polymer non-returnable containers that can provide tight connection between the lid and the body and are certified as IP-2 packaging according to NP-053-16.

Polymer containers are widely used in industry. Their use for RW disposal (in particular, low-level spent ion-exchange resins — LIER) has already been proposed in [31] (see Figure 5).

Figure 5. IP-2 type polymer packaging for low-level spent ion-exchange resins (left) and a polymer insert in the NZK container for intermediate-level SIER (right) [31]

The role of enclosing structures (disposal compartments)

In the long-term safety assessments of near-surface disposal facilities at the sites of JSC UEIP, FSUE PA Mayak and JSC SCC, it was conservatively assumed that radionuclide migration through the concrete walls of the disposal compartments in a period of up to 100 years is possible due to diffusion processes, from 100 to 300 years — due to diffusion and filtration, and over 300 years — mainly due to filtration. This corresponds to the service life of the compartments, which in the design documentation (DD) has been set to 100 years in accordance with [32, 33, 34].

This migration model is applicable only if the disposal compartments remain leakproof during this period. However, these requirements were not specified in the DD. Protection of containers from water is provided by other EBSs: waterproofing materials of the covering and underlying screens, as well as buffer materials.

Thus, in near-surface disposal facilities at the sites of JSC UEIP, FSUE PA Mayak and JSC SCC, the disposal compartments are thought to implement rather constructive function providing orderly emplacement of RW packages, preventing soil collapse on the packages and some external influences.

Operation of trench-type RW long-term storage facilities [35] has shown that loss of waterproofing capacity due to long-term freezing and thawing cycles occurring in the covering screen, waste package flooding, leaching of radionuclides and release of radioactive water through penetrations in the walls of the compartments in the contour zone of the storage facilities are seen as most probable mechanism of RW delocalization.

In this regard, construction of disposal compartments, which are not hermetic on their own, do not fully correspond to their safety function.

Another open issue is the use of concrete compartments for the joint disposal of RW Class 3 (20 % of the volume) and RW Class 4 (80 % of the volume). It should be taken into account that RW Class 4 involves large inventories of very low-level waste. Graded approach to the disposal of different class RW differing significantly in their potential hazard levels will reduce the cost of their disposal in near-surface disposal facilities.

Selection of EBS clay materials for near-surface disposal facilities

Clay materials used for waterproofing purposes in near-surface disposal facilities play a very important role in the EBS system since the main waterproofing requirements for RW packages are associated with the covering and underlying screens, as well as the buffer material, and water flow through them is considered as the main mechanism of radionuclide migration. Therefore, vivid scientific discussions are held to specify relevant requirements to clay materials [36—38].

In recent years, bentonite-based materials have been specifically developed to provide the isolation of radiation-hazardous facilities and RW disposal [39—41], R&Ds are underway to identify optimal characteristics of the buffer materials.

Various clay materials (the so-called greasy rumpled clay, a mixture of bentonite and kaolin, a cement-bentonite mixture, bentonite clay powder) are used under near-surface repository designs implemented at the sites of JSC UEIP, FSUE PA Mayak and JSC SCC. Comparative analysis of these materials is presented in [37].

According to these data and considering the unique self-sealing ability of bentonite, this material and mixtures based on it are seen as most promising materials that can be used to ensure the waterproofness of near-surface disposal facilities. Moreover, it should be noted that decision-making regarding particular materials should be implemented based on the evaluation of alternative options and a comparison criterion, which deserves particular comprehensive study.

Discussion of the results

This article briefly analyzes engineering solutions proposed for the disposal of conditioned RW Class 3 and 4 in above-ground, shallow and underground near-surface disposal facilities operated and designed in Russia and abroad.

Optimal solution for RW Class 3 disposal is seen in the development of above-ground and underground near-surface disposal facilities, for RW Class 4 — of above-ground near-surface disposal facilities.

Shallow near-surface disposal facilities can be used for RW Class 3 disposal if these are sited in low-permeable (clay) or well-permeable (sand) soils in arid areas with low groundwater levels.

Regardless of the repository type, it's considered feasible to dispose of RW Class 3 and 4 separately with different sets of safety barriers provided. Their designs should be selected and substantiated in the design documentation taking into account the characteristics of the RW packages and the engineering surveys performed for the considered near-surface repository site.

RW Class 3 should be disposed of in reinforced concrete containers with metal or polymer inserts complying with the safety rules for the transportation of radioactive materials and acting as elements of the repository safety system.

Polymer containers of KRAD, KMZ and NZK-type or standard 0.2 m^3 barrels meeting the requirements established for IP-2 type packages are recommended for RW Class 4 disposal (instead of expensive metal ones).

Bentonite-based materials should be used to provide the waterproofing capacity of near-surface disposal facilities. The requirements associated with the composition and characteristics of these materials should be specified under relevant R&D.

To unify design solutions for near-surface repositories, it is recommended to develop standard design solutions for above-ground, shallow and underground near-surface disposal facilities, as well as the criteria enabling the selection of repository types, which can be used as a basis for the development of the design documentation.

References

1. *Materialy obosnovaniya litsenzii na ehkspluatatsiyu pervoi ocheredi statsionarnogo ob"ekta, prednaznachennogo dlya zakhoroneniya radioaktivnykh otkhodov — pripoverkhnostnogo punkta zakhoroneniya tverdykh radioaktivnykh otkhodov, otdeleniya "Novoural'skoe" filiala "Severskiy" FGUP "NO RAO"* [Materials of a license application for the construction (reconstruction) of a near-surface radioactive waste disposal facility for solid radioactive waste, Novouralsk department of FSUE NO RAO's Seversk branch] — URL: http://www.norao.ru/ecology/mol/ (accessed on 20.04.2021).

2. *Federal'nyi zakon ot 11 iyulya 2011 goda № 190-FZ "Ob obrashchenii s radioaktivnymi otkhodami i o vnesenii izmenenii v otdel'nye zakonodatel'nye akty Rossiiskoi FederatsiI"* [Federal Law No. 190-FZ of July 11, 2011 On the Radioactive Waste Management and Amendments to Certain Legislative Acts of the Russian Federation].

3. *Materialy obosnovaniya litsenzii na razmeshchenie i sooruzhenie pripoverkhnostnogo punkta zakhoroneniya tverdykh radioaktivnykh otkhodov 3 i 4 klassov, Chelyabinskaya oblast', Ozerskii gorodskoi okrug* [Materials of a license application for the siting and construction of a surface disposal facility for solid radioactive waste of classes 3 and 4, Chelyabinsk Region, Ozyorsk City District]. — URL: http://www.norao.ru/ecology/mol/ (accessed on 20.04.2021).

4. Materials of a license application for the siting and construction of a surface disposal facility for solid radioactive waste of classes 3 and 4, Tomsk Region, urban district ZATO Seversk. — URL: http://www.norao.ru/ecology/mol/ (accessed on 20.04.2021).

5. *O kriteriyakh otneseniya tverdykh, zhidkikh i gazoobraznykh otkhodov k radioaktivnym otkhodam, kriteriyakh otneseniya radioaktivnykh otkhodov k osobym radioaktivnym otkhodam i k udalyaemym radioaktivnym otkhodam i kriteriyakh klassifikatsii udalyaemykh radioaktivnykh otkhodov* [On criteria used to categorize solid, liquid and gaseous waste as radioactive waste, criteria used to categorize radioactive waste either as special (non-retrievable) radioactive waste or retrievable radioactive waste and classification criteria for retrievable radioactive waste]. Resolution of the Government of the Russian Federation No. 1069 of 19.10.2012. Collection of the legislation of Russian Federation, 2012, no. 44, art. 6017.

6. Classification of Radioactive Waste. IAEA Safety Standards. General Safety Guide GSG-1.

7. NP-093-14. *Kriterii priemlemosti radioaktivnykh otkhodov dlya zakhoroneniya* [Acceptance criteria for radioactive waste disposal].

8. NP-055-14. *Zakhoronenie radioaktivnykh otkhodov, printsipy, kriterii i osnovnye trebovaniya bezopasnosti*

[Disposal of radioactive waste. Principles, criteria and basic safety requirements].
9. NP-069-14. *Pripoverkhnostnoe zakhoronenie radioaktivnykh otkhodov, trebovaniya bezopasnosti* [Near-surface disposal of radioactive waste. Safety requirements].
10. NP-016-05. *Obshchie polozheniya obespecheniya bezopasnosti ob"ektov yadernogo toplivnogo tsikla (OPB OYATTS) s izmeneniyami, vnesennymi prikazom Federal'noi sluzhby po ehkologicheskomu, tekhnologicheskomu i atomnomu nadzoru ot 28.07.2014 No. 326, zaregistrirovannym Minyustom Rossiiskoi Federatsii 28.08.2014 No. 33890* [General Safety Provisions for Nuclear Fuel Cycle Facilities as amended by Order № 326 of the Federal Service for Environmental, Technological and Nuclear Supervision of July 28, 2014, registered by the Ministry of Justice of the Russian Federation on August 28, 2014 No. 33890].
11. NP-031-01. *Normy proektirovaniya seismostoikikh atomnykh stantsii* [Standards for the design development of earthquake-resistant nuclear power plants].
12. SP 2.6.1.2612-10 (OSPORB-99/2010). *Osnovnye sanitarnye pravila i normativy obespecheniya radiatsionnoi bezopasnosti* [Basic sanitary rules and regulations on radiation safety].
13. SanPiN 2.6.1.2523-09 (NRB-99-2009). *Normy radiatsionnoi bezopasnosti* [Radiation safety standards].
14. RB-117-16. *Otsenka dolgovremennoi bezopasnosti punktov pripoverkhnostnogo zakhoroneniya radioaktivnykh otkhodov* [Long-term safety assessment of near-surface radioactive waste disposal facilities].
15. NP-100-17. *Trebovaniya k sostavu i soderzhaniyu otcheta po obosnovaniyu bezopasnosti punktov zakhoroneniya radioaktivnykh otkhodov* [Requirements on the structure and the content of a safety analysis reports for radioactive waste disposal facilities].
16. https://gnssn.iaea.org/RTWS/general/Shared%20Documents/Waste%20Management/Feb%202015%20WS%20on%20LLW%20disposal/Day%202)%20Hungary.pdf (accessed on 01.09.2021).
17. McKenney D. E. Hanford's Radioactive Mixed Waste Disposal Facility. Fifth international conference on radioactive waste management and environmental remediation, Berlin (Germany), 3—9 Sep. 1995.
18. Planning and operation of low level waste disposal facilities. International Symposium on experience in the planning and operation of low level waste disposal facilities, Vienna, 17—21 June 1996.
19. http://www.nrwdi.org.za (accessed on 20.04.2021).
20. Dutler M., Vervialle J. P., Charton P. Present issues for Centre de la Manche disposal facility. TOPSEAL 2006, Transactions. European Nuclear.
21. Sorokin V. T., Pavlov D. I. Tekhnologii okonchatel'noi izolyatsii radioaktivnykh otkhodov: evropeiskii opyt i tendentsii [Technologies of radioactive Waste disposal: European experience and trends]. *Radioaktivnye otkhody — Radioactive Waste,* 2018, no. 4 (5), pp. 24—32.
22. Tsebakovskaya N. S., Utkin S. S., Kapyrin I. V. *Obzor zarubezhnykh praktik zakhoroneniya OYAT i RAO* [The overview of foreign practices of radioactive waste and spent fuel disposal]. Moscow, Komtekhprint Publ., 2015. 208 p.
23. Beigul V. P., Pavlov D. I. Sravnenie al'ternativnykh skhem zakhoroneniya RAO klassa 1 v sostave PGZRO [Comparison of alternative layouts for the disposal of class 1 radioactive waste in a deep disposal facility]. *Atomic Energy 2.0.* — URL: https://www.atomic-energy.ru/articles/2019/11/12/98998 (accessed on April 20, 2021).
24. Dorofeev A. N., Bol'shov L. A., Linge I. I. et al. Strategicheskii master-plan issledovanii v obosnovanie bezopasnosti sooruzheniya, ehkspluatatsii i zakrytiya punkta glubinnogo zakhoroneniya radioaktivnykh otkhodov [Strategic Master Plan for R&D Demonstrating the Safety of Construction, Operation and Closure of a Deep Geological Disposal Facility for Radioactive Waste]. *Radioaktivnye otkhody — Radioactive Waste,* 2017, no. 1, pp. 32—41.
25. Sorokin V. T., Pavlov D. I. Tekhnicheskie aspekty sozdaniya regional'nogo punkta zakhoroneniya radioaktivnykh otkhodov. Retrospektiva podkhodov [Technical Aspects of Creating a Regional Disposal Facility for Radioactive Waste. Retrospective of the Approaches]. *Radioaktivnye otkhody — Radioactive Waste,* 2018, no. 1 (2), pp. 15—20.
26. Low-Level Radioactive Waste Repositories: An Analysis of Costs — Nuclear Energy Agency, OECD, 1999.
27. Pavlov D. I., Il'ina O. A. O sistemnom podkhode k vyboru bar'erov bezopasnosti dlya zakhoroneniya RAO klassov 3 i 4 [On a System Approach to the Selection of Safety Barriers for the Disposal of Radioactive Waste Class 3 and 4]. *Radioaktivnye otkhody — Radioactive Waste,* 2020, no. 3 (12), pp. 54—65. DOI: 10.25283/2587-9707-2020-3-54-65.
28. Gataullin R. M., Davidenko N. N., Sviridov N. V., Sorokin V. T. et al. *Konteinery dlya radioaktivnykh otkhodov nizkogo i srednego urovnei aktivnosti* [Containers for low- and intermediate-level waste]. Edited by Sorokin V. T. Moscow, Logos Publ., 2012. 255 p.
29. GOST 13950-91. *Bochki stal'nye svarnye i zakatnye s goframi na korpuse* [Steel barrels welded and rolled with corrugations on the body].
30. NP-053-16. *Pravila bezopasnosti pri transportirovanii radioaktivnykh materialov* [Safety guide for the transportation of radioactive materials].
31. Sorokin V. T., Prokhorov N. A., Pavlov D. I. Tekhnologiya konditsionirovaniya otrabotavshikh ionoobmennykh smol metodom termovakuumnoi sushki

[Spent Ion Exchange Resin Conditioning Technology Based on Thermal Vacuum Drying Method]. *Radioaktivnye otkhody — Radioactive Waste,* 2021, no. 2 (15), pp. 39—48. DOI: 10.25283/2587-9707-2021-2-39-48.

32. SP 63.13.330-2012. *Betonnye i zhelezobetonnye konstruktsii* [Concrete and Reinforced Concrete Structures].

33. GOST 27751-2014. *Nadezhnost' stroitel'nykh konstruktsii i osnovanii* [Reliability of Building Structures and Foundations].

34. GOST 31384-2008. *Zashchita betonnykh i zhelezobetonnykh konstruktsii ot korrozii* [Protection of Concrete and Reinforced Concrete Structures from Corrosion].

35. Prozorov L. B. Otsenka sostoyaniya khranilishch RAO pripoverkhnostnogo tipa [Assessing the state of near-surface RW storage facilities]. *Bezopasnost' yadernykh tekhnologii i okruzhayushchei sredy — Safety of nuclear technologies and the environment,* 2011, no. 2.

36. Martynov K. V., Zakharova E. V., Dorofeev A. N. et al. Ispol'zovanie glinistykh materialov dlya sozdaniya zashchitnykh bar'erov radiatsionno opasnykh ob"ektov [Use of Clay Materials in the Construction of Protective Barriers at Radiation Hazardous Facilities]. *Radioaktivnye otkhody — Radioactive Waste,* 2020, no. 3 (12), pp. 39—53. DOI: 10.25283/2587-9707-2020-3-39-53.

37. Il'ina O. A., Krupskaya V. V., Vinokurov S. E., Kalmykov S. N. Sovremennoe sostoyanie v razrabotkakh i ispol'zovanii glinistykh materialov v kachestve inzhenernykh bar'erov bezopasnosti na ob"ektakh konservatsii i zakhoroneniya RAO v Rossii [State-of-Art in the Development and Use of Clay Materials as Engineered Safety Barriers at Radioactive Waste Conservation and Disposal Facilities in Russia]. *Radioaktivnye otkhody — Radioactive Waste,* 2019, no. 4 (9), pp. 71—84. DOI: 10.25283/2587-9707-2019-4-71-84.

38. Krupskaya V. V., Biryukov D. V., Belousov P. E. et al. Primenenie prirodnykh glinistykh materialov dlya povysheniya urovnya yadernoi i radiatsionnoi bezopasnosti ob"ektov yadernogo naslediya [The use of natural clay materials to increase the nuclear and radiation safety level of nuclear legacy facilities]. *Radioaktivnye otkhody — Radioactive Waste,* 2018, no. 2 (3), pp. 30—43.

39. TU 08.12.22-302-01424676-2020. *Poroshok bentonitovyi dlya sozdaniya inzhenernykh bar'erov bezopasnosti pri konservatsii i zakhoronenii radioaktivnykh otkhodov, yadernykh i radiatsionno opasnykh ob"ektov. Tekhnicheskie usloviya* [The use of bentonite powder in the construction of engineered safety barriers for the conservation and disposal of radioactive waste, nuclear and radiation-hazardous facilities. Engineering specifications].

40. TU 08.12.22-301-01424676-2020. *Glina bentonitovaya droblenaya dlya sozdaniya inzhenernykh bar'erov bezopasnosti pri konservatsii i zakhoronenii Radioaktivnykh otkhodov, yadernykh i radiatsionno opasnykh ob"ektov. Tekhnicheskie usloviya* [The use of bentonite crushed clay in the construction of engineered safety barriers for the conservation and disposal of radioactive waste, nuclear and radiation-hazardous facilities. Engineering specifications].

41. TU 08.12.22-004-87299967-2020. *Materialy geosinteticheskie bentonitovye rulonnye dlya sozdaniya inzhenernykh bar'erov bezopasnosti pri konservatsii i zakhoronenii radioaktivnykh otkhodov, yadernykh i radiatsionno opasnykh ob"ektov. Tekhnicheskie usloviya* [The use of geosynthetic bentonite roll materials in the construction of engineered safety barriers for the conservation and disposal of radioactive waste, nuclear and radiation-hazardous facilities. Engineering specifications].

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