ON THE SELECTION OF A DISPOSAL OPTION FOR LOW- AND INTERMEDIATE-LEVEL WASTE

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The paper provides an overview of various options for the near-surface disposal of low- and intermediate-level radioactive waste. It assesses the engineered safety barriers proposed in these concepts, examining their functions and designs.

The study suggests that the current practice of disposing of radioactive waste in shallow near-surface facilities can potentially be replaced by surface disposal methods. It discusses different engineering designs proposed for surface repositories, particularly focusing on preventing water accumulation within the repository structures. Additionally, it summarizes the results of safety assessments related to these design concepts.

Keywords: *radioactive waste, near-surface disposal facilities, engineered safety barriers, radioactive waste containers, disposal cells, bottom layers, anti-bathtub system, inspection galleries.*

Introduction

Currently, the only near-surface radioactive waste disposal facility (NSDF) in operation in the Russian Federation (RF) is located in the restricted administrative and territorial entity (RATE) of Novouralsk [1]. Several additional facilities are planned to handle the entirety of the accumulated and generated Class 3 and 4 radioactive waste (RW). According to [2], the National Operator for RW Management (NO RAO) is considering the North-Western, Central, Ural, and Siberian federal districts as potential sites for new NSDFs. In line with these plans, designs for NSDFs have been developed for two sites in RATE Ozersk [3] and RATE Seversk [4]. The total design capacity of the three facilities in Novouralsk, Ozersk, and Seversk is projected to be 425,000 m^3. The existing and anticipated volumes of low- and intermediate-level radioactive waste (LLW and ILW) in the Russian Federation necessitate the development of new NSDFs that consider existing projects.

Similar design options have been proposed for all three disposal facilities (RATE Novouralsk, Ozersk, Seversk): Class 3 and 4 RW is disposed of in shallow reinforced concrete structures (disposal compartments) with Class 3 RW in NZK reinforced concrete containers in the bottom tier and Class 4 RW in metal containers (KRAD and KMZ drums) in the upper tier.

This method complies with the requirements set forth in Government Resolution (GR) No. 1069 of October 19, 2012 (as amended by GR No. 1929 of October 29, 2022), specifically the requirement for Class 3 RW disposal at a depth of up to 100 m (in shallow NSDFs, they are placed below the ground surface with Class 4 RW packages above). However, this approach has several significant disadvantages.

The following engineering solutions raise questions regarding this type of final disposal design:

- The preference for the shallow disposal concept lacks the advantages of both underground and above-ground disposal options and is susceptible to groundwater inflows into the disposal compartments [5];

- Different classes of RW are disposed of in the same compartments, with ILW packages placed beneath LLW packages. In the event of water inflow into the compartments, the waste with higher specific activity could be submerged [6], [7];
- Waterproofing designs (clay retainers) do not include systems to protect the disposal compartments from rainwater and groundwater seepage, thus preventing the "bathtub" scenario [8].

It has also been noted [7] that designs involving RW disposal in protective concrete containers within concrete compartments require appropriate feasibility studies since these factors significantly impact RW disposal costs.

Due to expected amendments [9] to GR No. 1069 in 2024, which will revise the approaches to RW classification based on disposal methods, it seems prudent to reevaluate the proposed near-surface disposal methods for LLW and ILW, focusing on costs and safety.

Possible Near-Surface RW Disposal Methods

An overview of international RW disposal practices [10], [11] reveals a variety of methods for final LLW and ILW disposal.

Waste is disposed of in surface and underground facilities at various depths, utilizing different engineered safety barrier (EBS) materials and designs.

Figure 1 illustrates potential basic near-surface LLW and ILW disposal concepts and EBS designs, offering a variety of final NSDF design options.

To select the optimal design option, the disposal facility should be associated with a specific site, including quantitative safety and cost assessments for each option (e.g., modeled radionuclide transport, calculated exposure, capital, and operating costs). This task is challenging and labor-intensive if all possible design options for an NSDF are to be assessed.

Therefore, the advantages and disadvantages of various near-surface disposal methods and specific

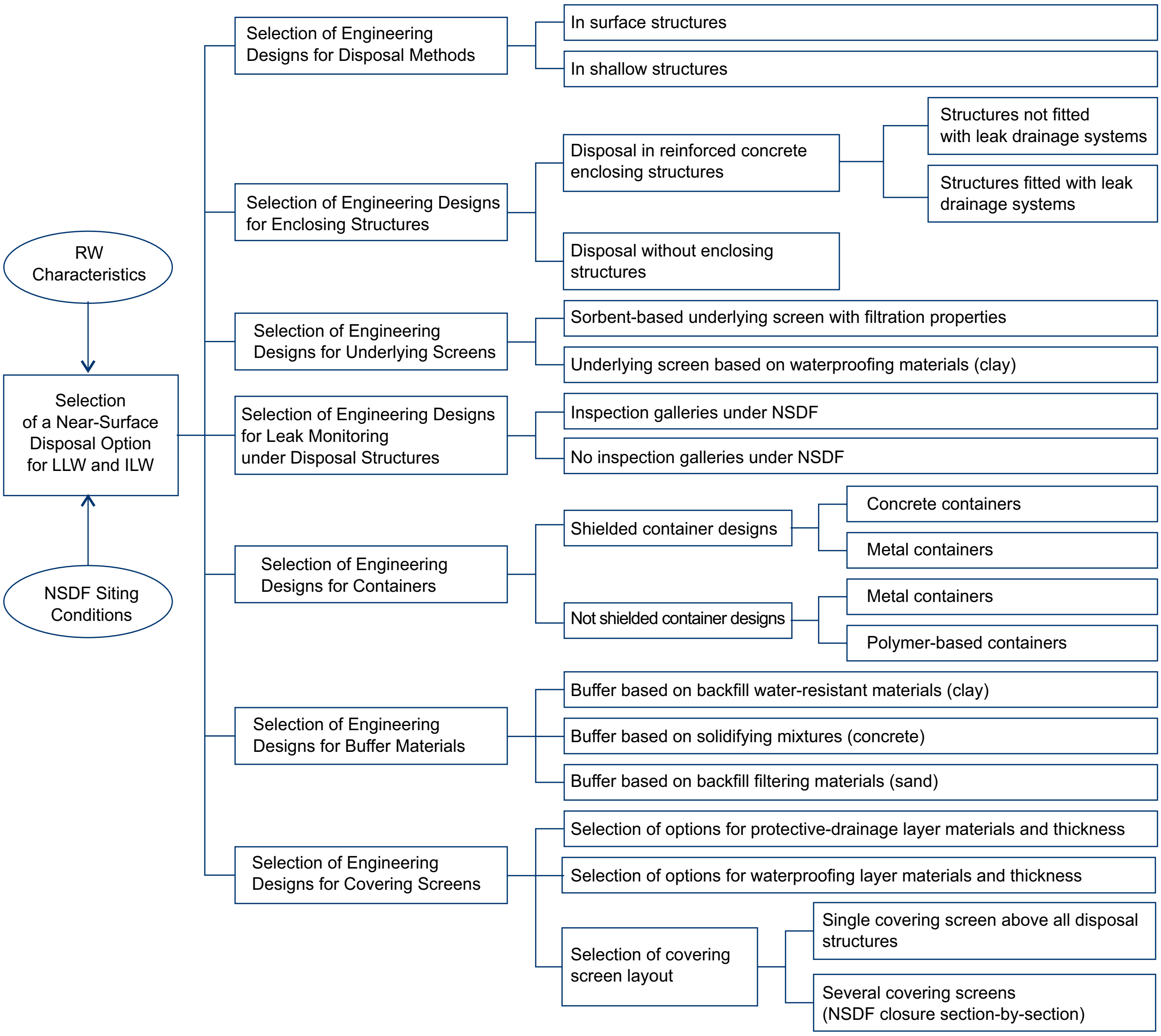


Figure 1. Various engineering designs for near-surface LLW and ILW disposal concepts

EBS design features are compared below. This comparison screens out less promising options without requiring prior cost assessments and radionuclide transport calculations. Broad estimates were used to evaluate fundamentally different options (particularly concerning underlying screen designs) when qualitative comparisons provided no clear preference.

The rationale behind selecting the preferred buffer and covering screen materials was not considered in this article.

Considerations for Shallow and Surface RW Disposal Methods

Advantages and disadvantages of near-surface RW disposal methods have been quantitatively compared in several studies [5], [11]. Shallow disposal methods, which have certain disadvantages inherent to surface disposal designs, lack the specific advantages of underground methods [5].

A study [11] reviewing European RW disposal facility designs notes a trend away from constructing shallow NSDF structures. Of over twenty LLW and ILW NSDFs developed in European countries, only three are of this type: Drigg (UK) [12], Dukovany (Czech Republic) [13], and Buryakivka (Ukraine) [14].

No such trend is observed in the US, where NSDFs buried relative to the ground surface are sited in areas with low groundwater and precipitation levels. For example, at the Andrews waste disposal facility (Texas, USA), waste is disposed of in a pit buried relative to the ground surface within Dokum clay formations approximately 200 m thick [15]. The low groundwater level (over 150 m below the base of the disposal structures) and arid climate (annual precipitation of less than 40 cm) allow RW disposal without EBS protection from precipitation. The excavated rock (red clay) is used to backfill voids and build a covering screen (Figure 2).

Figure 2. RW repository in the US (Texas)

In temperate and humid climates, RW disposal in pits or trenches must address several issues, such as drainage of seepage water and fluctuations in groundwater levels.

According to [16], trench RW disposal was attempted in France, but the packages became flooded, leading to the selection of surface disposal for LLW and ILW (Figure 3) [17]. This method is now replicated in several other countries, including Spain, Lithuania, and South Korea. Russian practice of shallow RW disposal in XX-century repositories, with no intention of future waste retrieval, yielded similar results: most RW packages became flooded over time (operating experiences discussed in [18]).

The French RW disposal experience in surface and shallow NSDF reveals the following common problems for these facilities:

- The sinking of the bottom part relative to the grade site level drives the RW packages closer to aquifers, thereby increasing the probability of radionuclide releases into the environment compared to surface disposal. It also heightens the risk of flooding due to rising groundwater levels and perched water emerging in the off-season.
- High precipitation levels typical for most sites necessitate regular water pumping from the disposal compartments during the waste emplacement stage. Shallow NSDF designs exclude gravity drainage systems, requiring the development of pressure system designs for water drainage during waste emplacement.

Surface and shallow RW disposal methods have also been compared in some Russian publications [5], [11]. According to [5], shallow NSDFs can be feasibly sited in low-permeable (clay) or highly permeable (sand) soils in arid areas with low groundwater levels. In most other regions of the Russian Federation, the surface RW disposal method is advised as more universal (compared to shallow disposal) and cost-effective (compared to disposal at several tens of meters depth).

On the Selection of Enclosing NSDF Structures and Container Designs

According to NP-069-14 Near-Surface Radioactive Waste Disposal. Safety requirements, NSDF structure designs, composition, and properties of safety barriers must be discussed and justified in the design documentation. The design documentation for the three disposal facilities in RATE Novouralsk, Ozersk, and Seversk provides for ILW disposal in concrete NZK containers installed into concrete enclosing structures, i. e., disposal compartments. In the long-term safety assessments (LSA) of these

Figure 3. Evolution of RW disposal methods in France (top left: RW disposal in shallow trenches, 1969; top right: disposal on an above-ground concrete foundation without shelter structures, 1985; bottom: modern surface RW disposal facility with concrete compartments, shelter structures, and inspection galleries for leak monitoring; bottom right: sampling operations in the inspection gallery) [16], [17]

NSDFs, both containers and compartments are considered barriers restricting radionuclide transport, differing only in their service lives (NZK — 300 years, compartments — 100 years).

The differences in the service life of enclosing structures and containers, and their overall impact on NSDF safety and cost, have been discussed in several publications. In [19], it was proposed to impose certain requirements on enclosing structures to make the characteristics of compartments similar to those of NZK containers (service life of at least 300 years, tightness, etc.). In [20], it was proposed to transition from reinforced concrete containers to metal ones. In [21], it was suggested to dispose of NZK containers without any enclosing structures (compartments). The importance of these issues was highlighted in [22], raising global questions about the performance of the Unified State System for RW Management.

It is noteworthy that international RW disposal practices consider both EBS system designs that include enclosing structures and those that do not.

Figure 4 shows examples of NSDF designs developed abroad, with reinforced concrete RW packages installed into reinforced concrete compartments and without such structures.

In regions where the climate permits waste disposal operations in the open air, waste is disposed of without enclosing structures. In regions where protection from atmospheric impacts is necessary, compartments provide suitable enclosing structure designs. Additionally, NSDF enclosing structures are equipped with systems designed to drain precipitation during the package emplacement stage and usually feature special devices to drain possible leaks throughout the active control stage.

They are incorporated into NSDF designs developed in France, Belgium, Spain, Bulgaria, Japan, and are engineered to prevent water accumulation in the RW package array in case the covering screen loses its integrity. In the Belgian NSDF design concept [24], this system is called an antibathtub system, preventing overflow scenarios. The feasibility of this option and its potential application in Russian NSDF designs has been discussed in another article [27].

In some NSDF, to maintain leak drainage devices, inspection galleries are included as part of the enclosing structure designs (Figure 5).

This design layout, based on Figure 5, requires regular maintenance operations and special engineering solutions at the repository closure stage (e.g., backfilling all voids with buffer materials).

Figure 4. RW disposal in reinforced concrete RW packages with and without enclosing structures: top left – France [23]; top right – Belgium [24]; bottom left – USA, South Carolina [25]; bottom right – South Africa [26]

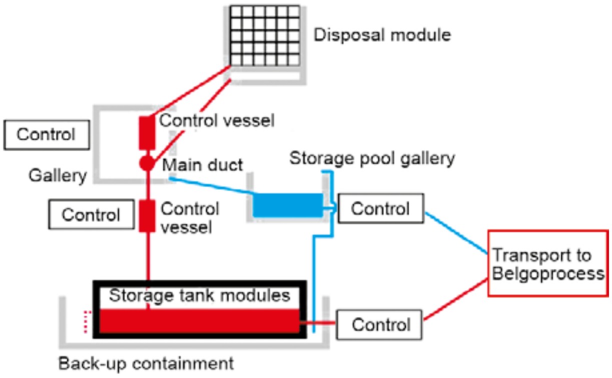


Figure 5. Layout of a leak drainage system in a NSDF with an inspection gallery and various engineering structures (tanks, pipelines) designed to collect and monitor drained water (Belgium [24])

Moreover, prior to closure, certain conditions may promote radionuclide transport between the interface of the underlying screen and the external environment (leak collection tank).

For this reason, some countries opt for disposal facility designs that exclude disposal galleries altogether. Examples include the modern NSDF designs developed in Lithuania [28] (facility B-25) and Slovenia/Croatia [29] (RW from the Krško NPP), which are based on the French model: they forgo inspection galleries but utilize passive leak drainage systems that prevent overflow scenarios through specific designs of the enclosing systems that gradually infiltrate precipitation seeping into the compartments. At the post-closure stage, runoff is monitored by regular sampling through observation wells drilled around the disposal facilities' perimeter.

Drainage systems integrated into enclosure structure designs abroad, and their varied approaches to use (or non-use), highlight the differences between their functions and those of containers within an EBS system of an NSDF (Table 1).

Table 1. Functions of Enclosing Structures and Containers

Basic Functions of Enclosing Structures	Basic Functions of Containers
• Biological protection of personnel at the NSDF site (according to OSPORB-99/2010, the dose rate on the structure surface should not exceed 0.6 μSv/h) • Acting as embankment (formwork) into which the buffer material is backfilled • Preventing man-made and natural impacts from closure of disposal compartments until covering screen installation • Accommodating mechanical loads on containers exerted by the covering screen	• Biological protection during transportation and handling (according to NP-053-16, the dose rate on the container surface should be less than 2 mSv/h) • Preventing water ingress to the waste contained in the containers • Preventing radionuclide releases from the waste in the containers

Considering the climatic conditions inherent in Russia and the actual state of its container fleet, the national legal framework (OSPORB-99/2010, NP-064-17, NP-053-16, NP-069-14, NP-093-14) mandates that both enclosing structures and protective containers be incorporated into NSDF designs. However, decisions regarding specific design features and their service life should be made individually for each NSDF, taking into account the specific activity levels and the radionuclide inventory of the waste to be disposed of (Figure 6).

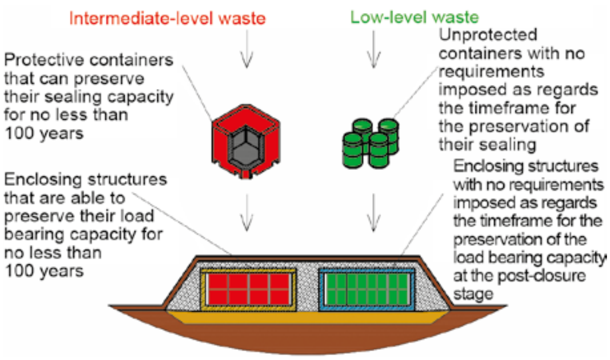


Figure 6. Selection of disposal options based on disposal depth, container, and enclosing structure designs considered under promising NSDF designs in Russia

If the packages are not designed to withstand the loads exerted by the covering screen, then the enclosing structures in a compartment should provide load-bearing capacity for the time period specified for a container as a barrier retarding radionuclide releases. The load-bearing capacity preserved by reinforced concrete enclosing structures (absorbing the loads from the covering screen) within a timeframe similar to the sealing capacity provided by an NZK container (about 300 years) seems entirely achievable, given that their designs account for a safety margin.

These structures should incorporate gravity drainage systems designed to collect and monitor discharges during the RW emplacement stage. NSDF designs should feasibly include a passive drainage system to handle possible leaks (without inspection galleries), thus preventing overflow scenarios at the post-closure stage. If the enclosing structure designs incorporate leak drainage systems, no sealing capacity requirements might be imposed on them.

Possible Underlying Screen Designs

Considerations regarding leak drainage from enclosing structures are directly related to the engineering solutions provided in their designs and the underlying screen material.

Russian NSDF designs [1], [3], [4] consider clay as the basic raw material, using a so-called clay retainer arranged along the perimeter and bottom of the disposal structures to waterproof the repository. In case of possible leaks through the covering screen, the underlying screen will prevent contaminant releases into groundwater. However, these designs do not allow for the removal of such contaminants, leading to their accumulation in the disposal area. Moisture transfer models developed for such NSDF [6] indicate that at least the lower tiers of waste packages are expected to become flooded.

Some NSDF designs developed abroad consider underlying screens made of natural sorbents that allow water to pass through while absorbing radionuclides released with the water flow. For instance, the EBS designs provided in the NSDF designs developed for the Kozloduy NPP (Bulgaria) employ this approach (Figure 7).

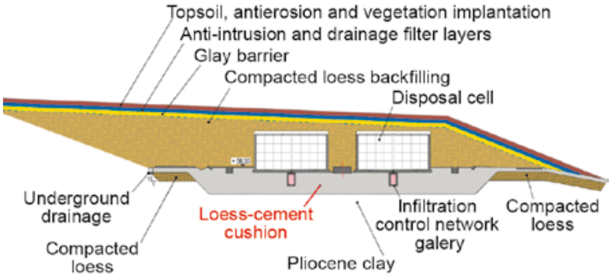


Figure 7. Upper and bottom screen designs of a NSDF at Kozloduy NPP [30]

The loess-cement cushion layer of the engineered backfill barrier, featuring selected site soils (e. g., loess rocks found on the site) mixed with 5 % cement, provides a geotechnically stable foundation for this NSDF and increases the thickness of the unsaturated zone beneath the disposal cells. Acting together, these components, in accordance with their absorption capacities, form a sorption barrier that retards the release of radionuclides dissolved in water flowing through the bottom of the disposal structures.

Radionuclide transport calculations for the NSDF at the Kozloduy site indicated the high performance of the underlying loess-cement sorption screen. Figure 8 shows data on the ^{14}C radionuclides released from the reinforced concrete disposal structures into this layer (red line) and from it into the underlying sand layers (blue line).

The high sorption capacity of the loess-cement material may provide significant retardation of radionuclide releases, amounting to hundreds or even thousands of years.

In addition to loess-cement, other materials have been used for sorption layers. For example, the VLLW disposal facility at the Oskarshamn NPP in

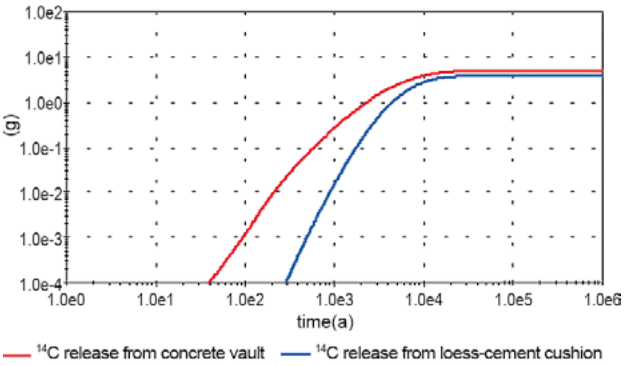


Figure 8. ^{14}C retardation by the loess-cement underlying screen [30]

Sweden employs a foundation fitted with drainage grooves, directing water towards a sorption layer composed of a mixture of shell rock, sand, and peat. This layer facilitates water seepage and radionuclide absorption (Figure 9).

Figure 9. VLLW disposal facility at the Oskarshamn NPP, Sweden [31]

In the Russian Federation, a mixture of sand (60 %) and zeolite (40 %) was proposed for the sorption layer in the underlying screen designs developed for a temporary VLLW storage facility in Andreev Bay [32].

Multivariate transport calculations have been performed for this facility, considering three layout options for the sorption layer: on the edge of the concrete foundation slab, partially underneath it, and atop of it (Figure 10).

The calculation model assumed that radionuclide releases into the environment were driven by their leaching from VLLW by seepage flow, followed by transfer along the concrete foundation slab to its edge. Subsequently, the radionuclides were released into the sorption layer and then into the aquifer, where they moved horizontally with groundwater flows.

Radionuclide transport calculations performed for the temporary VLLW storage facility in Andreev Bay have demonstrated high performance of sorption layer designs. Table 2 summarizes the calculation results, providing two numbers for the specific activity: the upper one corresponds to a distance of 2 m from the edge of the slab, the lower one to a distance of 10 m from the slab. The water release provides data on radionuclide releases from the repository into the aquifer in the upper line, whereas the lower one corresponds to radionuclide releases into the Andreev Bay. Public exposure was estimated based on the calculation results according to which a release of 10^{10} Bq/year corresponded to a dose of approximately 10 μSv for both ^{90}Sr and ^{137}Cs.

Table 2 indicates that the sorbing layer reduces possible public exposure associated with 90Sr by approximately 2 times, whereas the one associated

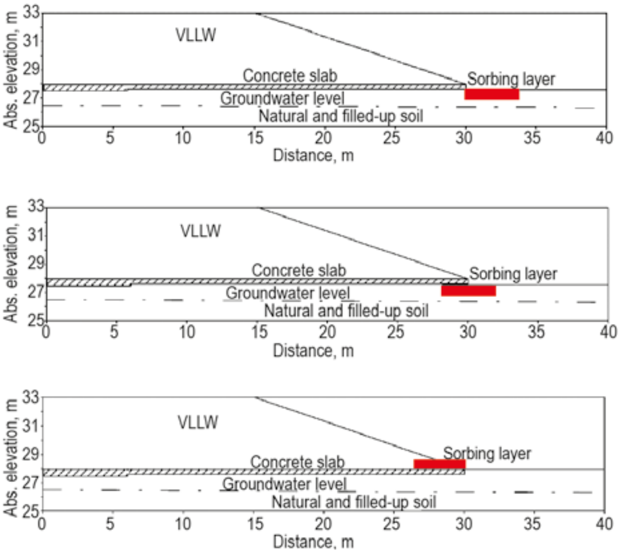


Figure 10. Layout options for the sorption layer proposed in the designs of a temporary VLLW storage facility in the Andreev Bay: on the edge of the concrete foundation slab, partially underneath, and atop of it

Table 2. Calculated radionuclide transport from temporary VLLW storage facility in the Andreev Bay considering different sorption layer layouts [32]

Calculated parameter	Calculation type for ^{90}Sr and ^{137}Cs					
	Sorption layer at the edge of the foundation slab		Sorption layer partially under the foundation slab		Sorption layer above the foundation slab	
	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Specific activity, Bq/l	0.95 0.62	0.25 0.12	0.57 0.38	0.12 0.065	0.66 0.45	0.10 0.05
Release into water, Bq/year	$8.0 \cdot 10^5$ $6.2 \cdot 10^5$	$2.4 \cdot 10^5$ $1.2 \cdot 10^5$	$5.0 \cdot 10^5$ $3.6 \cdot 10^5$	$1.2 \cdot 10^5$ $6.0 \cdot 10^4$	$5.0 \cdot 10^5$ $4.5 \cdot 10^5$	$7.5 \cdot 10^4$ $5.0 \cdot 10^4$
Exposure dose, μSv/year	$6.2 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$	$6.0 \cdot 10^{-5}$	$4.5 \cdot 10^{-4}$	$5.0 \cdot 10^{-5}$
Maximum exposure time, years	30	70	30	70	40	100

with ^{137}Cs can be reduced by 4 times; if fitted partially under the slab or on the edge of it, the exposure due to ^{90}Sr may be reduced by approximately 4 times and the one due to ^{137}Cs — by 10 times.

Proper choice of underlying screen materials is also viewed as a relevant task for the future LLW and ILW NSDF in Russia. Discussed below are the radionuclide transport calculations performed considering different layout options for the underlying screen made of water-resistant material and a natural sorbent having filtration properties.

Radionuclide Transport Estimated Considering Various Underlying Screen Material Options

To perform comparative assessments, a conventional disposal facility sited on ground surface level with a net design capacity of 10,000 m^3 of RW was considered (Figure 11).

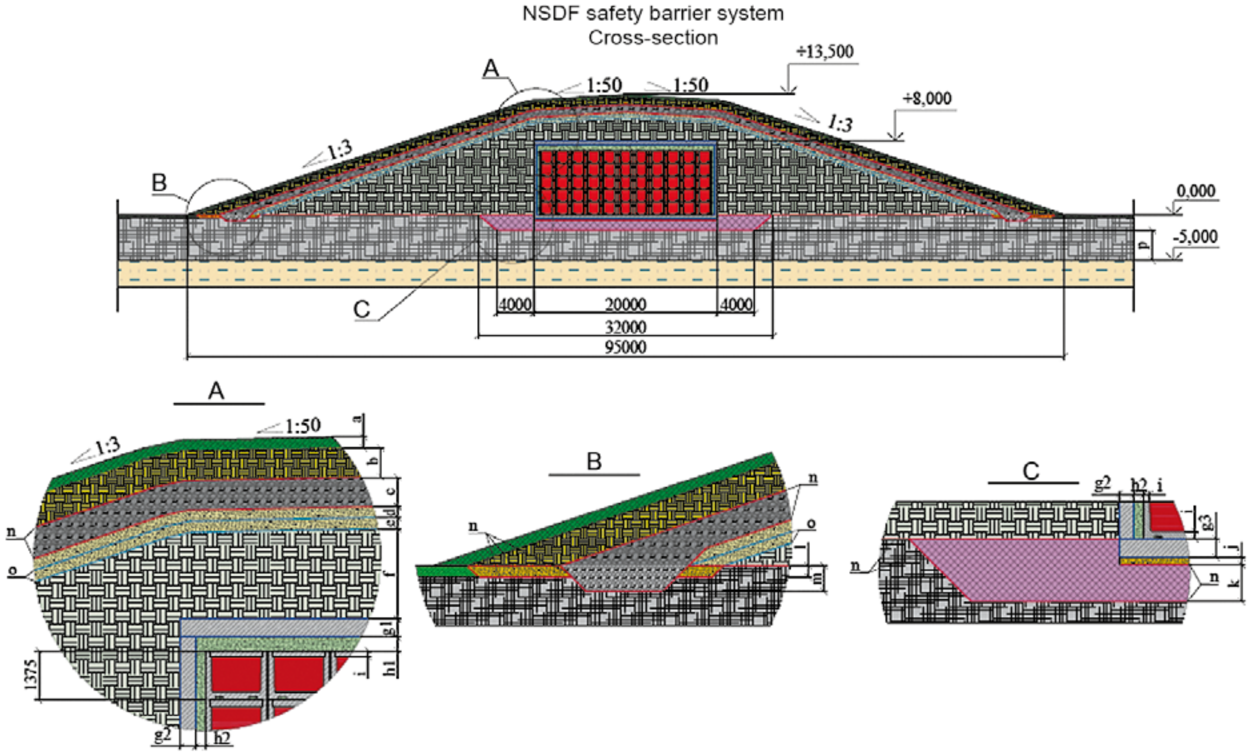
It was assumed that the RW packages are loaded into a single reinforced concrete module of 20 × 8 × 220 m.

The NSDF covering screen is a system of waterproofing, protective, and drainage soil and vegetative layers.

For option 1, the underlying screen was made of clinoptilolite (a natural sorbent with filter material properties), for option 2, it was made of clay with water-resistant properties.

Hydrogeological conditions assumed for the model:

- a near-surface 5-m-thick sandy loam layer starting directly from the soil-vegetative layer;
- the sandy aquifer being located at a depth of over 5 m, extending to a depth of up to 7 m from the ground surface level;



List of NSDF structure elements

Element	Name	Thickness, mm
a	Fertile soil layer and grass cover	300
b	Clay-sand layer	800
c	Protective and drainage layer of crushed stone	500
d	Sand layer (sand cushion between crushed stone and bentomat)	300
e	Sand layer providing foundation for the bentomat layers	300
f	Clay layer	2200 (not less than)
g1	Upper compartment slab	500
g2	Compartment slab	400
g3	Bottom compartment slab	500
h1	Buffer material layer above the RW packages	625
h2	Buffer material layer between RW packages and compartment walls	300
i	Container walls, bottom and lid	150
j	Sand cushion acting as a foundation for the compartments	300
k	Option 1 – Clinoptilolite layer Option 2 – Clay layer	1,200
l	Sand cushion for surface leveling under the covering screen	300
m	Drainage ditch filled with crushed stone	500
n	Geotextiles	2–3
o	Bentomat	5–7
p	Sandy loam (host rock from underlying screen "k" to aquifer)	3,200

Figure 11. NSDF layout considered as a basis for comparative calculations focused on radionuclide transport in different underlying screen materials

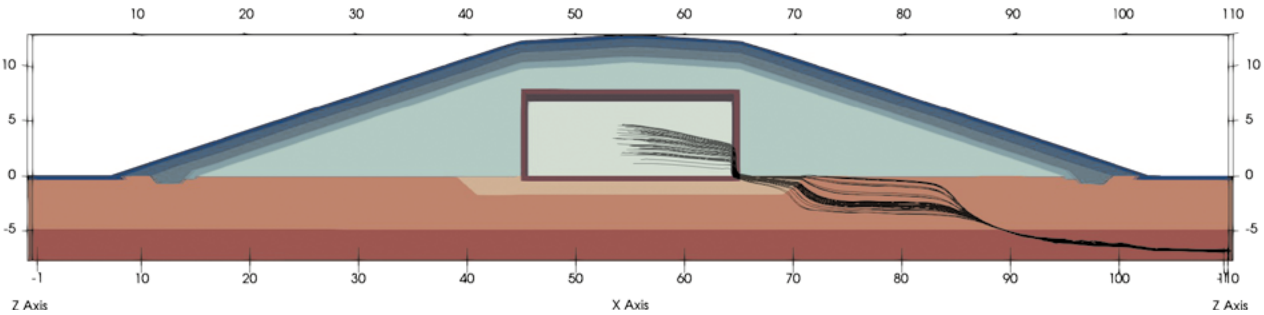


Figure 12. ^{129}I *transport tracers based on the modeled option with clinoptilolite (black color – ^{129}I transport trajectories)*

- clay formations occuring at a depth of over 7 m.

Considering the geometry of the computational domain, a triangular-prismatic mesh containing 37,220 cells was used for modelling purposes.

In the modelling process, the field-specific stationary saturated-unsaturated filtration problem was solved numerically, with advection, dispersion, and diffusion processes having been simulated. Calculations were performed using the certified GeRa software package [33].

In the calculations, the load was specified for four radionuclides (^{60}Co, ^{137}Cs, ^{90}Sr, ^{134}Cs) with a total specific activity of $2.75 \cdot 10^7$ Bq/kg, with the largest contribution provided by ^{137}Cs ($2.7 \cdot 10^7$ Bq/kg). The specific activity and radionuclide composition roughly correspond to those of cemented intermediate-level liquid radioactive waste resulting from the operation of nuclear power plants with WWER-1200 reactor units. **The modeling results demonstrated that under both options none of the radionuclides managed to escape the disposal zone,** which could be explained by their short half-life and high sorption characteristics.

Based on the above, it can be argued that both clay and a clinoptilolite-based sorbent may be considered as appropriate underlying screen materials in surface NSDF designs. Due to its filtration properties, clinoptilolite provides water drainage from the disposal zone and prevents the overflow scenario.

Since the calculations focused on short-lived radionuclides provided no clear information on possible radionuclide transport required to evaluate the bottlenecks in the designs of surface NSDF, further calculations were performed to evaluate the transport of a weakly sorbed radionuclide with a long half-life (^{129}I) and a total activity of 10^{10} Bq (Figure 12).

Based on the tracer transport calculated for ^{129}I, it can be assumed that leaks should be advisably drained in such a way that the water containing radionuclides and seeped into repository is distributed over the entire surface area of the underlying screen. Therefore, concrete grades with low water resistance can be used to build its foundation, and the underlying screen area can be extended.

Conclusion

Various methods of near-surface RW disposal have been evaluated, evidencing a close relationship between the decisions made regarding the RW disposal depth, the choice of the enclosing structure designs, materials of the underlying screen,s and drainage systems. This once again supports the comprehensive approach that should be used when considering these issues.

Upon enactment, the amendments introduced to the GR No. 1069 [9] are expected to set the stage for further improvement of the approach currently emerging in the Russian Federation, providing for the development of shallow NSDF.

The following engineering solutions are considered feasible for the design and construction of new disposal facilities for LLW and ILW with a limited long-lived radionuclide inventory in Russia:

- NSDF siting at the ground surface level with the RW packages being emplaced at a level not lower than the site level;
- introduction of various engineered barriers for ILW and LLW disposal (disposal in separate modules, the durability of which, in terms of the load-bearing capacity, should correspond to the service life of containers installed in these modules);
- passive systems draining possible leaks (with no inspection galleries provided for in the designs) and preventing water accumulation in the disposal compartments and the overflow scenario.

These requirements are quite similar to the engineering solutions introduced in LLW and ILW disposal designs in France, Spain, Belgium, Lithuania, South Korea and some other countries. Nevertheless, there's a conceptual difference which accounts for the installation of a seepage-sorption underlying screens, preventing the use of complex leak collection systems with inspection galleries and providing the passive disposal safety.

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