# ON A SYSTEM APPROACH TO THE SELECTION OF SAFETY BARRIERS FOR THE DISPOSAL OF RADIOACTIVE WASTE CLASS 3 AND 4

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*The article describes different designs and materials of engineered safety barriers (ESB) for radioactive waste disposal facilities, systematizes the functions and technical specifications of EBS and based on a system approach proposes safety barrier materials and designs for the disposal of radioactive waste class 3 and 4.*

**Keywords:** *radioactive waste, surface and near-surface disposal facilities, engineered safety barriers, containers for radioactive waste disposal, bentonite, system approach.*

## Introduction

Federal Law on Radioactive Waste Management… [1] states that depending on RW class, conditioned waste should be isolated either in near-surface or deep disposal facilities. FTP on Nuclear and Radiation Safety provides for the development of several regional near-surface disposal facilities (RWDF) for RW class 3 and 4 (given the classification system based on [2]).

In 2016, first near-surface RWDF located at UECC site was commissioned in the Russian Federation. FSUE National Operator for Radioactive Waste Management has started the development of designs for RWDFs to be sited at PA Mayak, JSC SCC, in the Krasnoyarsk Territory and other regions. During the design development, various design options and materials for engineered barrier construction are being considered. However, the challenge associated with the decision making on the safest, most feasible and cost-effective options still remains to be addressed.

Design development, construction and operation of final disposal facilities is seen as a relatively new focus area for Russian nuclear industry with no unified approaches yet been established and no sufficient experience and knowledge accumulated to date. Given the envisaged scope of RW disposal operations, the task of finding optimal engineering solutions enabling the selection of RWDF structures and materials for engineered safety barrier (EBS) construction based on a systematic approach seems to be quite relevant.

## The need for a systematic approach

Development of RWDF designs for RW Class 3 and 4 entails a decision-making on a number of engineering solutions to be applied. RWDFs for low- and intermediate-level waste, being operated or developed in different countries, differ by the disposal depth (surface, shallow and underground,

Figure 1), EBS materials (steel, concrete, bentonite, etc.), capacity (up to 1 million $m^3$), geography (climate, geology) and other characteristics. Some engineering solutions being in place at existing RWDFs were chosen based on the historical background or particular aspects of the national regulatory framework, social and political factors. For this reason, selection of reference final RW disposal technologies seems to be quite challenging.

A number of studies, for example [3-5], has attempted to evaluate RW disposal designs and EBS materials available in different countries, to identify relevant trends in RW disposal methods and optimal design solutions. However, general abundance of approaches has been recognized suggesting that feasibility studies addressing each particular case are required.

Taking into account the variety of disposal methods, commitment to RF regulatory framework when it comes to the selection of relevant materials and methods, the scale of environmental and economic consequences driven by such decisions, decision-making on RWDF designs can be viewed as a classic one done under uncertainty.

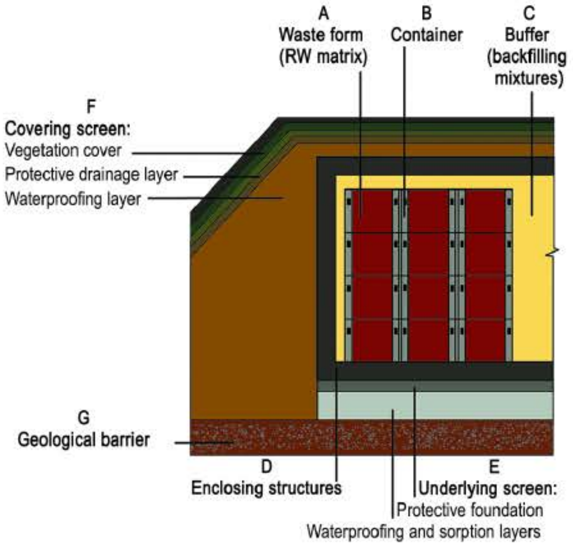
In this case, the decision-making on an optimal solution seems worth to be guided by a systematic approach [6], since RWDF is considered as a set of interrelated and interconnected elements (barriers) forming an integral unity — a system.

Regulatory provisions also indicate the need for a systematic approach to be applied in RWDF design development [7, 8]. However, in the Russian Federation, system analysis methods in the field of RW disposal are not mature enough, whereas general methods, for example, such as [9], should be properly adapted to the existing needs. If properly refined, the bellow proposals on the selection of engineering solutions as regards safety barriers for the disposal of RW Class 3 and 4 based on a systematic approach can be used in RWDF feasibility studies and design development.

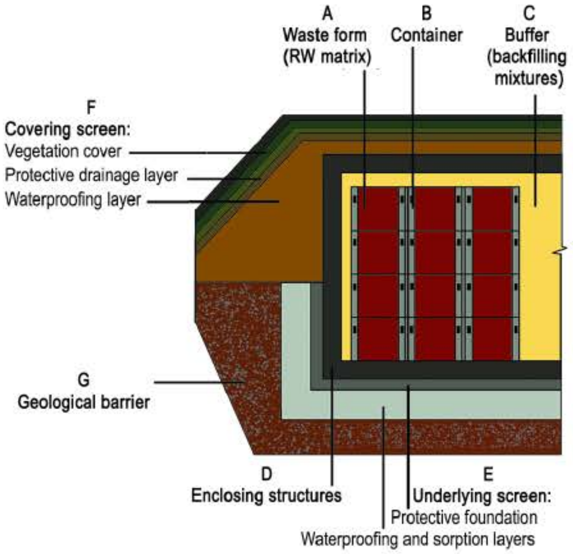
## About RWDF safety barrier system

Table 1 summarizes the data on RWDF safety barrier system (SBS) and its elements (barriers) with relevant indications of their particular design purposes. These generally correspond to the designs of an RWDF operated at UECC site [10], as well as those to be sited at SCC [11] and PA Mayak [12] sites.

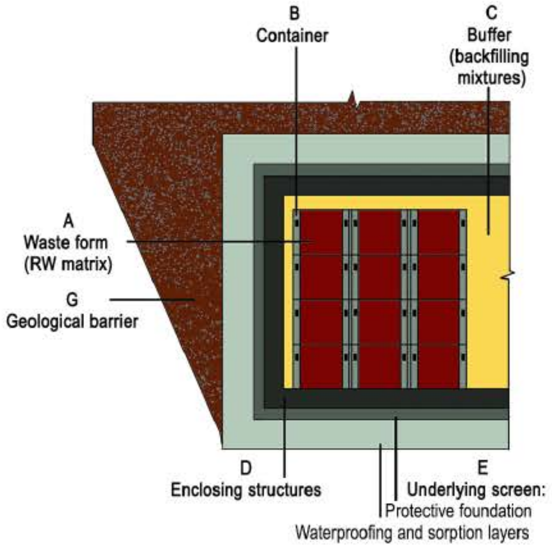
Various requirements are imposed on the safety barriers to ensure the specified functions. General requirements for near-surface RWDF can be found in [13], those dealing with disposal packages — in [14], considering some RW disposal matrices — in [15] and [16]. Federal norms and rules and safety



a) Surface disposal type structure



b) Shallow disposal type structure



c) Underground disposal type structure

*Figure 1. Typical design layout of final disposal facilities for RW Class3 and 4*

***Table 1. List of elements (protective barriers) in the disposal system intended for RW Class 3 and 4***

| Indi-cation | Barrier | | Purpose |
|---|---|---|---|
| A | Waste form (RW matrix) | | • Radionuclides are captured within the matrix material |
| B | Container | | • Prevents water seepage.<br>• Slows down radionuclide releases from matrix material or the primary package.<br>• Biological shielding |
| C | Buffer (backfilling mixtures) | | • Elimination of voids and free spaces.<br>• Sorption of radionuclides released from the containers.<br>• Prevention of water accumulation or (depending on safety-important design solutions) high drainage capacity to minimize the time of water contact with RW packages.<br>• Establishment of a neutral environment preventing container degradation |
| D | Enclosing structures | | • Obstruct technogenic and natural impacts.<br>• Slow down the release of radionuclides into the geological barrier or into the covering and underlying screens.<br>• Biological shielding |
| E | Underlying screen | Protective foundation | • Obstructs technogenic and natural impacts.<br>• Accommodation of mechanical loads from barriers A, B, C, D, F |
| | | Waterproofing and sorption layers | • Prevent water flows to barriers A, B, C, D.<br>• Sorb radionuclides released from barriers A, B, C, D |
| F | Overlying screen | Protective drainage layers | • Obstruct technogenic and natural impacts.<br>• Drain atmospheric precipitation and surface water flowing to the waterproofing layer |
| | | Waterproofing and sorption layers | • Prevent water flows to barriers A, B, C, D.<br>• Sorption of radionuclides releasing from barriers A, B, C, D (depending on safety-important design solutions) |
| | | Vegetation cover | • Establishment of a solid natural cover preventing the growth of shrubs and trees |
| G | Geological barrier ** | | • Prevents radionuclide migration in case of EBS degradation<br>• Obstructs technogenic and natural impacts |

*For surface and shallow RWDF.

**In case of surface and shallow RWDF, the geological barrier is not conservatively considered in the safety assessment, in accordance with the requirements stated in [13]

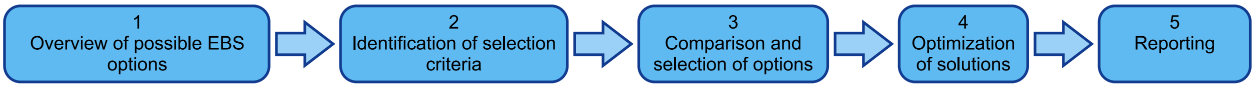


*Figure 2. Step-by-step decision-making flowchart*

guidelines in the field of atomic energy use [8, 17] provide comprehensive RWDF safety requirements implying that the major part of the requirements focused on EBS materials should be specified based on design documentation. Regulatory requirements for barrier materials and enclosing structures providing protective functions have not yet been developed. Summarizing the above, a fairly wide field of opportunities suggesting different engineering solutions under the decision-making on EBS selection is in place.

Given the efforts implemented to overview available disposal methods [3—5], Table 2 provides a most general matrix showing possible safety barrier options for RWDFs.

Obviously, such a matrix provides multiple combinations of engineering solutions. In this regard, the challenge of selecting an optimal design and EBS material can be reduced to a step-by-step flowchart shown in Figure 2.

Similar algorithm is used under well-recognized ALARA principle of radiation protection [18]

Selection criteria shall be specified not only for the EBS, but also for the entire disposal system in general, i. e. the best solution for each element (barrier) may not always be considered optimal for the entire SBS.

## About selection criteria

Each RWDF element fulfills its specific function in the disposal system and, accordingly, specific selection criteria are in place for each EBS in accordance with its design purpose.

Quantitative acceptance criteria for the safety barriers are not fully defined by the regulatory

*Table 2. Matrix of EBS options for RWDF*

| No. | Parameter | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E1 | E2 | F1 | F2 | F3 | G | H |
| | RW matrix | Container material | Backfilling (buffer) material | Enclosing structure material | Underlying screen material* | | Overlying screen material* | | | Bedrock | RWDF type |
| | | | | | Protective foundation | Waterproofing layer | Waterproofing layer | Protective drainage layer | Vegetation layer | | |
| 1 | Bitumen | Metal | Crushed bentonite | Concrete | Crushed stone | Bentonite clay | Bentonite clay | Crushed stone | Soil | Clays | Surface |
| 2 | Concrete | Concrete | Concrete | No enclosing structures | Sand | Bentomat | Bentomat | Sand | – | Crystalline | Shallow |
| 3 | Glass | Other (ceramics, polyethylene, etc.) | Cement-bentonite mixture | – | Gravel-sandy mixture | HDPE / LDPE geomembrane | HDPE / LDPE geomembrane | Gravel-sandy mixture | – | Salts | Underground (up to 100 m) |
| 4 | Ion-exchange resins | – | Sand | – | Concrete | Highly plastic clays with no requirements imposed on their mineral composition | Highly plastic clays with no requirements imposed on their mineral composition | Geocomposite drainage materials | – | Other | – |
| 5 | Salt melt | – | Crushed stone | – | – | Bitumen | Bitumen | - | – | – | – |
| 6 | Metal | – | Bentonite – kaolin mixture | – | – | – | – | - | – | – | – |
| 7 | | | Sandy-bentonite mixture | | | | | | | | |
| 8 | Other | – | Salt** | – | – | – | – | – | – | – | – |

*in case of surface and shallow RWDF

**in case of underground RWDF in salt formations

🟥 – some preferred options based on expert judgment

framework of the Russian Federation. Most of the characteristics that the RWDF elements shall comply with are specified in the design documentation (local acceptance criteria).

Table 3 presents quantitative parameters of safety barriers viewed as essential in terms of RW isolation.

Parameters 1—9 are considered essential for the analysis of RWDF barrier evolution, whereas parameters 8—15 are viewed as crucial in terms of assessing the radionuclide migration.

Table 4 exemplifies a quantitative assessment of some buffer materials.

Quantitative characteristics presented in Table 4 demonstrate considerable differences between the buffer materials. Decisions on which material to choose for buffer production and what requirements are to be imposed on it are made in the design documentation taking into account RWDF design, its siting conditions and the expected RWDF construction cost. It seems reasonable to develop industry-specific regulations and guidelines,

*Table 3. List of main quantitative criteria for EBS assessment*

| № | Parameter | Unit |
|---|---|---|
| 1 | Service life | year |
| 2 | Compressive strength | MPa |
| 3 | Radiation stability | Gr |
| 4 | Elastic modulus | MPa |
| 5 | Frost resistance, (−40 °C—+40 °C) | cycle |
| 6 | Swelling pressure (for bentonite) | MPa |
| 7 | Vapor permeability | mg/(m·h·Pa) |
| 8 | Water permeability ($K_{filtration}$) | m/day |
| 9 | Thickness | mm (m) |
| 10 | Dispersion | m |
| 11 | Density | g/cm$^3$ |
| 12 | Porosity (active, effective) | % |
| 13 | Distribution coefficient ($K_d$) for radiologically important radionuclides | m$^3$/kg (ml/g) |
| 14 | Diffusion coefficient for radiologically important radionuclides | m$^2$/s |
| 15 | Sorption capacity | mg/g (mol/g) |

***Table 4. Some quantitative criteria for buffer material assessment***

| Parameter | Protective barrier (buffer) | | | |
|---|---|---|---|---|
| | Bentonite clay | Concrete | Sand** | Kaolin clay |
| Service life, years | Not limited | Not less than 100 | Not limited | Not limited |
| Elastic modulus, MPa | 20–110 | $9{\cdot}10^3$–$4{\cdot}10^4$ | 40–130 | 20–110 |
| Frost resistance, (−40 °C – +40 °C), cycle. | Not limited | 100–1000 | Not limited | Not limited |
| Swelling pressure (for bentonite), MPa | 0,2–10* | – | – | – |
| Vapor permeability, mg / (m h Pa) | 0.04–0.06 | 0.02–0.04 | 0.15–0.2 | 0.04–0.06 |
| Water permeability ($K_{filtration}$), m/day | $10^{-8}$–$10^{-7}$ | $10^{-9}$–$10^{-7}$ | 1–10 | $10^{-5}$–$10^{-4}$ |
| Density, g/cm$^3$ | 1.8–2. 6 | 2.2–2.7 | 1.4–1.9 | 2.2–2.7 |
| Porosity, % | 30–60 | 10–15*** | 5–45 | 6–50 |
| Distribution coefficient ($K_d$) for radiologically important radionuclides, m$^3$/kg**** | $10^2$–$10^4$ | ~$10^3$ | Data n/a | $10^2$–$10^3$ |
| Diffusion coefficient for radiologically important radionuclides, m$^2$/s**** | $10^{-14}$–$10^{-11}$ | $10^{-14}$–$10^{-13}$ | Data n/a | $10^{-8}$ |
| Sorption capacity, mg/g | 0.8–1.5 | Data n/a | Data n/a | 0.02–0.10 |

* Swelling pressure is a characteristic applicable only for compacted (pressed) bentonite.
** Specifications are given for sand according to GOST 8736-2014.
*** For heavy concrete.
**** Ranges are provided for $^{90}$Sr, $^{137}$Cs.

including system requirements for EBS materials and recommendations on their application.

Qualitative assessment criteria are considered more applicable when it comes to RWDF design options. Table 5 provides a case study of such an assessment for RWDF.

In accordance with system analysis approach, chosen engineering solutions for each RWDF element may be judged effective based on certain key indicators representing the entire system as a whole. The main criteria allowing to assess the effectiveness of engineering solutions that form the disposal system as a whole can be divided into two types: safety criteria and economic criteria (see Table 6).

Comparison according to the criteria presented in Table 6 can be done if RWDF construction, operation and closure estimates are available along with a comprehensive safety assessment.

## Comprehensive safety assessment for near-surface RWDF

Particular method based on a systematic approach is used to assess the safety of near-surface RWDF [21]. General safety assessment requirements are

***Table 5. Advantages and disadvantages of RWDF structures (qualitative assessment criteria)***

| Advantages | Disadvantages |
|---|---|
| Surface | |
| • Low capital construction costs [19, 20]<br>• Less stringent requirements to site geology<br>• Simple transport and process flowchart for package emplacement | • Influence of seasonal temperature fluctuations<br>• Large safety exclusion area<br>• Sophisticated multi-layer cover screen design<br>• Covering screen maintenance is required<br>• Sensitivity to external influences (especially during emplacement) |
| Shallow | |
| • Same advantages as in case of the surface option, plus smaller area of cover screens | • Same disadvantages as for the surface option, plus:<br>- additional soil excavation;<br>- water intrusion is possible due to groundwater fluctuations |
| Underground/deep | |
| • Resistance to external impacts<br>• Lack of seasonal temperature fluctuations<br>• Availability of a geological barrier<br>• Small safety exclusion area (surface RWDF section) | • High capital construction costs [19, 20]<br>• Specific requirements to site geology<br>• Specific requirements to pulling and running equipment |

*Table 6. Criteria for SBS assessment*

| № | Unit | Criterion |
|---|---|---|
| | Safety criteria | |
| 1 | Specific (volumetric) activity in environmental medium | Bq/kg (Bq/m$^3$) |
| 2 | Intervention levels based on the content of specific radionuclides in water | Bq/kg |
| 3 | Personnel exposure doses | mSv/year |
| 4 | Population exposure doses | mSv/year |
| 5 | Radionuclide migration rate through EBS | m/year |
| 6 | Resistance to external influences | – |
| 7 | EBS degradation rate and its degree | – |
| 8 | Reliability of the technology | – |
| 9 | Referentiality | – |
| | Economic criteria | |
| 10 | Capital RWDF construction cost | RUB |
| 11 | RWDF operation cost | RUB/year |
| 12 | RWDF closure cost | RUB |
| 13 | Monitoring cost | RUB/year |
| 14 | Costs for RW packaging and transportation to RWDF site | RUB |
| 15 | Specific disposal cost | RUB/m$^3$ |
| 16 | Specific retrieval cost (if necessary) | RUB/m$^3$ |

stated under Russian regulatory framework, namely, in [8] and in IAEA standards [7].

Various computer codes are commonly used worldwide to calculate radionuclide migration: these allow to model radionuclide transfer in EBS, geosphere and biosphere, as well as the barrier degradation and RWDF evolution.

To systematize evolution scenarios, approaches based on the analysis of factors, events and processes (FEP) are applied globally in the safety case development practice. FEP lists involve hundreds and sometimes thousands of different combinations of factors, events and processes affecting RWDF evolution. Methodological aspects associated with FEP accounting in case of Russian RW disposal systems were summarized in [22].

Basically, results of comprehensive safety assessments are obtained via data processing by computer systems. Nevertheless, the calculations are preceded by time-consuming and routine operations performed to collect and systematize data on the radionuclide composition of waste subject to disposal, characteristics of SBS, RWDF site, analysis of evolution scenarios, etc. Figure 3 presents a basic summary of a mathematical computer modeling flowchart executed during safety assessments.

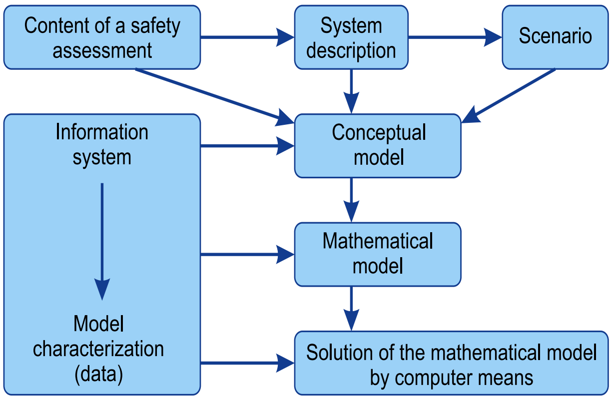


*Figure 3. Flowchart showing the development of a mathematical model and its calculation by computer means [21]*

Due to a great amount of work preceding the calculations, their complexity and multivariance of evolution scenarios, comprehensive safety assessment process cannot be fully automated. In this regard, it seems challenging to evaluate the use of all possible EBS materials and designs by enumerating them based on relevant computer calculations providing the results of a comprehensive safety assessment. It seems feasible to perform the calculations for various EBS options when most promising materials are already selected, for example, based on expert judgment.

## Cost assessments for various RWDF options

In addition to safety assessment, evaluation of costs associated with possible options is required to enable a comprehensive decision-making process on EBS selection.

Given the overriding priority of safety over relevant economic factors and an individual approach to each disposal facility, it seems reasonable to search for the most economical EBS structures and materials only if a significant economic effect can be achieved. Therefore, contribution of various EBS to RWDF capital and operating costs, as well as to the safety functions performed by the EBS shall be evaluated.

Table 7 summarizes the data on safety barriers and their functions based on estimate documentation for the RWDF in the Ozersk city (2019), OBIN (pre-investment feasibility study) materials for a RWDF in the North-Western Territorial District (2010), materials [23] and technical and commercial proposals provided by container equipment manufacturers indicating relevant contribution into disposal costs. Figure 4 shows the breakdown of capital and operating costs for the near-surface RWDF in the Ozersk city.

***Table 7. Data on safety barriers and their functions indicating relevant contributions to the disposal costs***

| RWDF element | | Main barrier functions | | | | | Contribution to disposal cost | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Radionuclide containment (sorption, immobilization, etc.) | Prevention of water accumulation (waterproofing or drainage (depending on safety option) | Biological shielding (personnel protection during operation and closure) | Obstructing man-made and natural impacts (precipitation, erosion, inadvertent intrusion, earthquake, aircraft crash, etc.) | Establishment of conditions reducing barrier degradation (backfilling, optimal pH level, balancing temperature fluctuations) | Capital RWDF construction cost | RWDF operating costs during waste emplacement period | RWDF closure costs | % of the total cost for EBS supply/installation /production |
| Safety barriers | Waste form (RW matrix) | ✓ | × | × | × | × | – | – | – | 5–15 % |
| | Container | ✓ | × | ✓ | × | × | – | – | – | 40–60 % |
| | Buffer | ✓ | ✓ | ✓ | × | ✓ | – | 20 % | – | 3–10 % |
| | Enclosing structures | ✓ | ✓ | ✓ | × | × | 51 % | – | – | 15–25 % |
| | Underlying screen | ✓ | ✓ | × | ✓ | × | 10 % | – | – | 3–5 % |
| | Overlying screen | ✓ | ✓ | × | ✓ | × | – | – | 90 % | 10–15 % |
| | Geological barrier | ✓ | × | × | ✓ | ✓ | – | – | – | – |
| Other RWDF elements not pertaining to EBS | | × | × | × | × | × | 39 % | 80 % | 10 % | – |

Notes:
1) RW immobilization (waste form) costs assumed based on [23].
2) Data on the cost of buffer, enclosing structures, underlying and covering screens were compiled based on estimate documentation for RWDF in Ozersk, OBIN materials for RWDF in the North-Western Territorial District, as well as other studies [19, 20, 24 ].
3) Container costs were calculated for four container types: KMZ; NZK-150-1.5P; KRAD-1.36, KRAD-3.0 based on engineering and commercial proposals of relevant supplying companies.

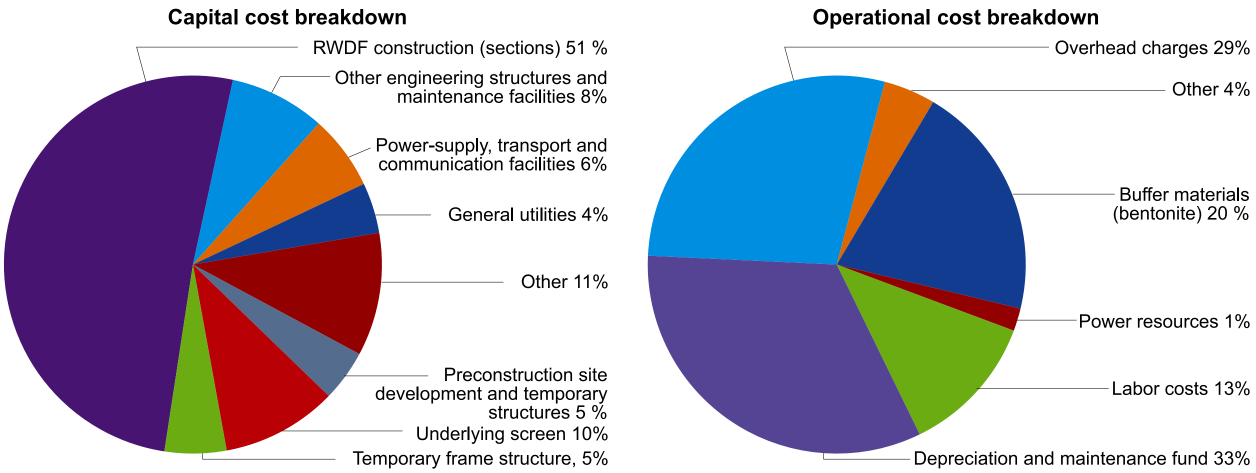


*Figure 4. Breakdown of capital and operational costs for a near-surface RWDF*

Evaluation of near-surface RWDF designs have revealed multiple duplication of barriers, especially in terms of radionuclide containment function. If proper quality of other barriers (for example, containers) is assumed, an option providing cost optimization as regards the enclosing structures can be considered since construction of this barrier requires more than half of capital RWDF construction costs and up to 25% of the total construction/supply cost of all barriers. Perhaps, in case of LLW disposal it would be feasible to replace the enclosing structures with clay-based buffer materials. Similar technologies were proposed in [25] and are also widely used in VLLW disposal practice.

In general, adequate economic assessment of various RWDF design options can be based on the calculated estimated costs specified for each option. However, all known methods of budgeting, including the analog one, most notably require serious engineering studies, which should reasonably consider most promising (namely already selected) solutions.

## Selection of most promising EBS materials and structures

Since low- and intermediate-level waste disposal practice has been implemented abroad for several decades with extensive international experience gained in this area to date, there is no need for complete comprehensive safety and feasibility assessments studying all possible combinations of EBS materials and designs. Even though no clear requirements on the selection of EBS materials and designs are provided in Russian regulations, the initial task of selecting most promising options can be addressed by systematizing the international practices and using already completed research on this topic (stage 1 of the selection process).

Selection of reference technologies associated with EBS materials and structures shall involve appropriate adaptation of these solutions to relevant RWDF siting conditions in the Russian Federation. For candidate sites located on the territory of PA Mayak, SCC, in the Krasnoyarsk Territory, the Arkhangelsk Region, relevant adjustments should be introduced to make up for severe climatic conditions and particular hydrogeological features of the sites. In particular, special attention should be paid to EBS frost resistance (in case of surface RWDF) and reliable waterproofing provided by the barriers.

Table 2 summarizes EBS materials and designs (highlighted in color) that were selected as most promising according to the authors based on the international disposal practices [3-5], recommendations on EBS application and relevant research [26—30].

A number of parameters that should be identified during comprehensive safety assessments should be further refined for these materials.

For example, for a bentonite buffer these parameters can be summarized as follows:

- content of base mineral (montmorillonite) governing impervious and sorption properties, and the content of impurities that can affect the system evolution in a negative way;
- cation exchange capacity;
- free swelling index, etc.

The decision-making process on the selection of optimal design options may prompt further improvement of the regulatory framework in the field of RW disposal, including the requirements associated with disposal containers and buffer materials.

## Conclusion

The paper suggests a method enabling the selection of EBS and RWDF design options based on a systematic approach. The method involves:

- development of a decision-making matrix;
- specifying the decision-making criteria1[1];
- selection of an expert team[1];
- comprehensive safety assessment of the selected options (feasibility study stage);
- disposal cost assessment accounting for solutions considered as being in line with relevant regulatory requirements[2];
- selection of the most appropriate option based on the calculations and estimates[2];
- optimization of the selected option[3] .

To calculate radionuclide migration and RWDF evolution scenarios, as well as to evaluate relevant costs, certain solutions were proposed enabling the selection of most promising EBS designs, including those associated with possible failure / optimization of redundant safety barriers.

The paper presents relevant contributions of each EBS to the cost of the entire EBS system considered helpful for barrier optimization.

Obviously, comprehensive safety and cost assessment of the proposed RWDF design options and identification of optimal requirements to the materials can be done only if adequate interaction between the representatives of scientific community, designers and manufacturing companies, namely of those producing container equipment and buffer materials, is provided.

The authors would like to express their hope for broad cooperation in this field.

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