FORECASTED TIMEFRAMES FOR THE LONG-TERM SAFETY OF NEAR-SURFACE DISPOSAL FACILITIES FOR RADIOACTIVE WASTE CALCULATED CONSIDERING VARIOUS SCENARIOS OF THEIR OPERATION

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The paper considers technical solutions providing the long-term safety of near-surface disposal facilities for radioactive waste (NSDF) based on engineered barrier systems (EBS). The system of isolating engineered barriers provides the long-term safety and reduces the spread of ionizing radiation and radioactive material from NSDF into the environment.

Keywords: *radiation safety, radioactive waste disposal, radioactive waste, ionizing radiation, engineered barriers, near-surface radioactive waste disposal, bentonite mats, clays, insulating material, radioactive waste containers, long-term safety, concrete structures, waterproofing screen.*

Degradation of safety barriers in radioactive waste (RW) disposal facilities is mainly driven by the inflow of either surface or groundwater to the bearing and insulating reinforced concrete and metal structures of the repositories which is followed by their chemical interaction with the waste form elements, structural units, their transformation, leaching/degradation of the binding elements in their material. In a long-term perspective (hundreds and thousands of years), water and salts dissolved in the water cause the degradation of load-bearing concrete structures constituting to the repository walls, supports, bottoms and roofs followed by the loss of their insulating capacity.

Russian and international practice provide for RW disposal in purposely-designed disposal facilities. According to the terminology adopted in the Federal Law of the Russian Federation of July 11, 2011 No. 190-FZ [1], a near-surface RW disposal facility is seen as a structure located at the ground surface level or at a depth of up to one hundred meters from the ground surface.

RW categorized as RW Class 3, 4 and 6 according to the Government Decree No. 1069 of October 19, 2012 [3] are subject to near-surface disposal (NSDF).

Federal norms and rules in the field of atomic energy use [4] state that a system of engineered and natural (geological) safety barriers shall be in place in a NSDF.

Structurally, a repository involves an engineered barrier system preventing the spread of ionizing radiation, nuclear materials and radioactive substances into the environment involving several safety barriers (Figure 1).

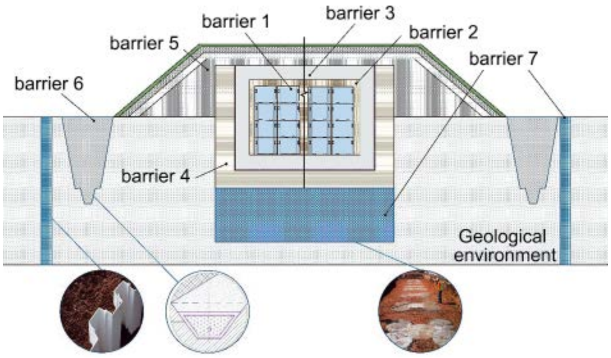


Figure 1. The system of engineered safety barriers in a repository: barrier 1 — containers with RW, barrier 2 — buffer material based on natural clays backfilling the voids in the disposal chamber, barrier 2 — concrete structures of walls, bottom and roof, barrier 4 — underlying cap, barrier 5 — covering waterproofing layer, barrier 6 — additional — drainage system, 7 - additional waterproofing barrier installed if needed

The first barrier (EBS 1) consists of NZK, KMZ, KRAD, ZhBU, ZHZK waste disposal containers, metal drums, filter containers and their analogues, produced according to accepted state standards.

The service life of reinforced concrete containers able to maintain their performance as engineered barriers (tightness, mechanical strength) under NSDF conditions should be at least 300 years (in accordance with paragraph 4.2 of GOST R 51824-2001 Protective Non-recoverable Containers for Radioactive Waste Made of Concrete-based Construction Materials).

Assuming the corrosion processes, the design life of metal containers accounts for at least 30—50 years (in accordance with the container ID characteristics and depending on the container type).

The second barrier (EBS 2) is a buffer bulk material based on natural clays used to fill the gaps in the chambers and between the waste containers. EBS 2 should provide the stability of the RW disposal chamber, reduce the radionuclide transport and limit water flows to RW containers or reduce their interaction time with water [4].

The time period during which a barrier shall maintain its waterproofing function was conservatively estimated as at least 300-500 years.

Nevertheless, the antimigration capacity can be preserved for a much longer time period due to high sorption capacities of clays and the low diffusion rate.

The third barrier (EBS 3) is represented by concrete structures constituting to the walls, bottom and roof considered as baseline repository design structures acting as essential elements of the near-surface disposal system providing its stability at the operational stage. Their service life is calculated in accordance with SP 63.13330-2012 Concrete and Reinforced Concrete Structures and GOST 27751-2014 Reliability of Building Structures and Foundations and should be not less than 100 years. Figure 2 presents the strength levels for concrete changing over time.

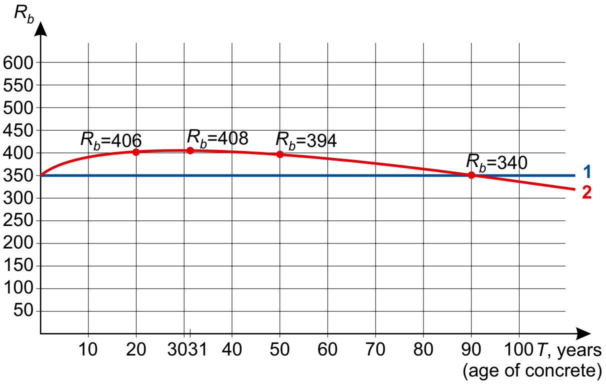


Figure 2. Predicted strength of concrete (R_b — uniaxial compressive strength): 1 — theoretical line showing the concrete strength buildup under normal conditions, 2 — changes in the concrete strength up to 100 years under specified operating conditions

Structures constituting to the third barrier made of concrete designed for civil engineering sector have a long-term strength of 100 years. In the EBS system, it is considered as the most short-lived barrier. Therefore, it is believed necessary to revise the parameters for concretes applied in the fabrication of structures constituting to the third barrier considering the fact that the long-term safety period assumed for all other repository barriers amounts to at least 300 years.

To increase this period for the structures constituting to the third barrier, concrete may be used to fabricate RW containers (type NZK-150-1.5P). Concrete Class B50 (M700, GOST 26633-91) with a compressive strength of 70 MPa, a density of 2.45 to 2.65 t/m^3 and a frost resistance and water resistance grade of at least F200 and W12, when applied in the structures constituting to the third barrier, may provide their long-term safety for up to 300 years [13].

The fourth barrier (EBS 4) is represented by the underlying cap and bentonite mats installed along the perimeter of repository structures (walls, bottom, roof) designed to provide the waterproofing capacity, to prevent water washout and radionuclide release into the host rocks. Thickness and properties of the underlying cap made of crumpled natural clay are selected based on calculations taking into account the properties and the composition of the host formations.

In addition to the clay retainer, bentonite mats were proposed in the EBS 4 designs with their waterproofing capacity provided for an unlimited service life with no integrity loss over time.

Their performance is provided by the high swelling capacity of bentonite upon its interaction with water.

Due to potential external and internal events expected at the post-closure stage, the waterproofing capacity was conservatively assumed to be maintained for at least 300—500 years, whereas, the radionuclide transport can be avoided for much longer time similar to EBS 2.

The fifth barrier (EBS 5) is a covering multifunctional waterproofing cap designed to protect the repository structures from atmospheric precipitation, intrusion of animals, plant roots and unintentional human intrusion.

It is applied from above to the surface of concrete roof slabs and typically involves a few layers (from the bottom to the top):

- waterproofing barrier prevents the seepage of atmospheric precipitation into repository structures;
- drainage barrier made of a gravel-sand mixture drains atmospheric precipitation from the surface;
- protective barrier made of crushed stone prevents mechanical damage of the waterproofing layer due to the intrusion of plants, animals and unintentional human activities;
- protective loam barrier with soil and vegetation cover maintains the moisture content in the underlying layers at a level necessary to prevent the clay cap from losing its waterproofing capacity due to drying and cracking, as well as to protect the underlying layers of the covering cap from erosion.

According to the designs, the waterproofing capacity of the covering waterproofing cap can be maintained for 300-500 years.

Additional engineered structures that may be proposed under near-surface disposal facility designs to increase the stability and extend the life of the main EBS structures are the drainage systems and impervious curtains.

The sixth barrier (EBS 6) is an additional barrier constituting of a drainage system draining surface and groundwater from the repository. It is designed in accordance with relevant siting conditions. The highest performance is achieved if there is a slope at the repository site. This system is a backup one installed in case of increasing seepage water, vadose water or groundwater flows (Figure 3).

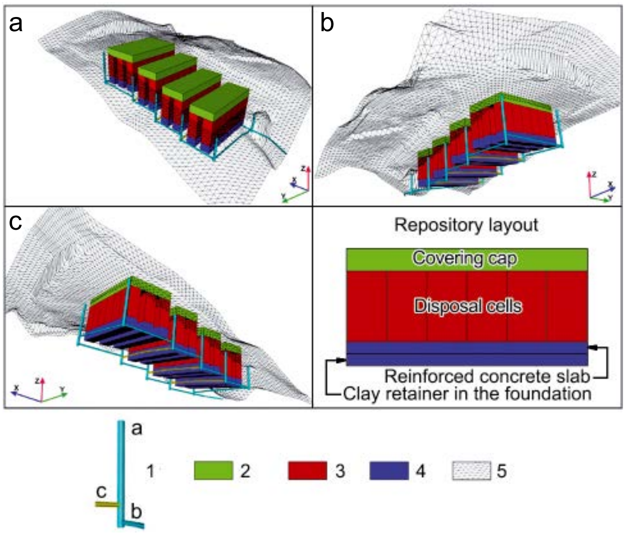


Figure 3. Example of a drainage system: 1 — double-circuit drainage: a well (a), drainage pipes of the external (b) and internal (c) circuits; 2–4 — repository: upper waterproofing cap (2), structure (3), reinforced concrete slab and clay retainer in the foundation (4); 5 — surface of the leveled landscape.

The geological medium is heterogeneous with some vadose water areas that can be found in its upper part: primarily these are locally distributed vadose waters and intermittent accumulations of gravitational waters build up on spatially unstable low-permeable soils above the first aquifer [5]. Vadose water availability is a factor that may potentially impact the key safety barriers, namely, their isolation capacity.

The seventh barrier (EBS 7), which is considered an additional barrier, can be installed both during repository construction and operation and around an already closed repository. It may be applied in case of changing climatic conditions, increased load on the main safety barriers due to vadose water, groundwater flows and involves the construction of sheet piling and soil-cement retainers around the modular structures (MS) of near-surface repositories.

Sheet piles are applied most commonly in the disposal practice: the service life of metal amounts to 11–30 years, composite piles may provide effective isolation capacity for much longer periods of time [11] (Figure 4).

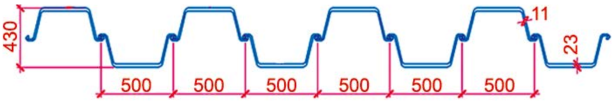


Figure 4. Structure of a sheet pile retainer

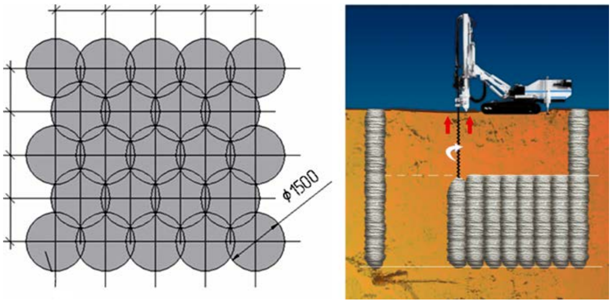
Applied sheet pile retainers may be exemplified as follows: polymer sheet piling (PVC) of the Mont Blanc type with soil stabilization (Figures 4, 5); composite sheet pilling based on the pultrusion method (PCM) installed in 2 rows and soil reinforcement, as well as combined: steel sheet pilling of the Larsen type and stabilization between the rows based on Jet-3 high-pressure jet-grouting method.

Figure 5. PVC sheet piling (construction of a facility in Skolkovo)

In accordance with GOST R 57365-2016/EN 12063:1999 Sheet Pile Walls, a sealed sheet pile retainer is characterized by a value reciprocal to the seepage resistance — a hydraulic permeability factor equal to $5 \cdot 10^{-10}$ m/s.

A sheet pile based on polymeric materials - carbon composite (CCM) and fiberglass are considered promising waterproofing barrier materials that may provide long-term waterproofing capacity protecting the repository from surface and ground water flows. These materials are basically not prone to corrosion, degradation in aggressive environments and have high physical and mechanical characteristics.

At repository construction stage, buried walls made of soil and cement are installed by high-pressure jet grouting method: these are established in the bottom part of repository structures by drilling to the groundwater level (Figure 6).



a b

Figure 6. Soil-cement buried wall in the bottom part of a MS: a — plan view, b — installation of the soil-cement wall

Soil-cement walls:

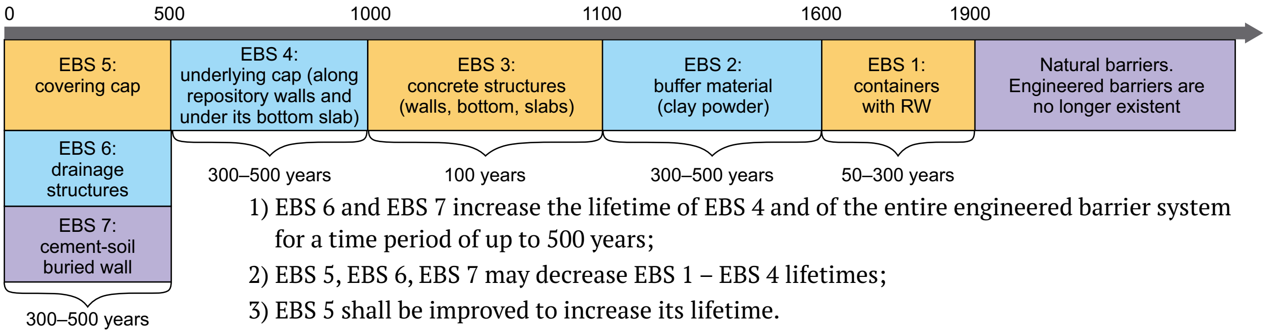
- a continuous impervious wall made of soil cement constructed based on the high-pressure jet grouting method Jet-1;
- a trench-type wall in soil made of B25, W12, F150 concrete.

As regards groundwater interaction with the clay cap, walls, bottom and lining of NSDF structures, the preliminary soil-cement wall with a CCM sheet pile may provide retention for 300—500 years.

Scenarios presenting the interactions occurring inside the engineered barrier systems are considered to identify dangerous patterns of events accounting for various combinations of such events.

A *simplified* scenario is assumed first: no materials containing moisture, biological substances, bacteria are present inside the waste containers; concrete structures of the walls are not wetted, i. e., there are no processes that may potentially drive EBS degradation from the inside. The engineered barriers may become *operational* only due to some external influences according to a sequence shown in Figure 7.

A scenario was considered assuming consecutive EBS failure with no account taken of the influence produced by the degradation of any previous barrier on the subsequent ones and the internal processes occurring in the barriers. In case of external influences (inflow of surface, ground waters), the



1) EBS 6 and EBS 7 increase the lifetime of EBS 4 and of the entire engineered barrier system for a time period of up to 500 years;

2) EBS 5, EBS 6, EBS 7 may decrease EBS 1 – EBS 4 lifetimes;

3) EBS 5 shall be improved to increase its lifetime.

Figure 7. Diagram showing step-by-step commissioning of engineered safety barriers over time (barrier degradation is caused by exposure to surface and ground water flows)

covering cap (EBS 5), drainage structures (EBS 6) and the cement-soil wall (EBS 7) are the first to get into operation. Upon their degradation (after 300—500 years), the waters start acting on the underlying clay cap along the repository walls and under its bottom part (EBS 4). Then (after 300—500 years), the waters start acting on concrete structures — walls, bottom, roof (EBS 3) made of concrete designed for basic civil construction (conservative option). Upon their degradation (after 100 years), waters start acting on the bulk buffer material filling the gaps between the MS walls and the RW containers, as well as the gaps between the containers (EBS 2). Container degradation (EBS 1) due to the waste contained inside the containers can be triggered by the internal processes occurring in the period of up to 300 years after RW emplacement into the repository. However, radionuclide transport from these containers is possible only upon water diffusion from EBS 2 to them.

The diagram (Figure 7) shows step-by-step *commissioning* of EBS elements. Under the *simplified scenario,* effective operation of the repository EBS elements providing for RW containment is assumed to account for 1050—1900 years. However, EBS 5 degradation in the first 300—500 years (assuming intense external influences) can cause water flows to the concrete EBS 3 structures with their degradation expected to start some 300—500 years earlier. Therefore, the degradation of all subsequent EBS, as well as of the entire repository is expected to take place earlier. The concrete EBS 3 structures may fail earlier (in 100 years) than the underlying EBS 4 cap protecting them from groundwater flows (in 300—500 years). There may be several combinations of different events. Relevant scenarios are considered below (assuming all kinds of combinations providing joint *operation* of different EBS) with the realistic ones identified among them.

1. Scenarios considering failure of a single EBS due to an external impact immediately upon repository closure (according to the diagram shown in Figure 7) and the impact of this event on the performance of other barriers (Table 1).

In combinatorics, this is the number of formal combinations made of 7 elements in twos. In accordance with the formula $C_n^m = \frac{n!}{m!(n-m)!}$ — there are 21 elements in total; Table 1 presents the comments true only for realistic combinations (12) corresponding to the diagram (Figure 7), as well as the expected result.

Only direct external influence was considered, the subsequent sequence of influences produced on other EBS elements and internal processes occurring in them were not analyzed, even though these were actually relevant. Filled in vertically are the EBS that failed, horizontally — those that were affected by this event, at their intersection - the expected result.

In accordance with Table 1 if immediately upon the repository closure:

- cement-soil wall fails (EBS 7): groundwater inflow into the drainage system gets more intense causing early siltation. The underlying clay cap enters

Table 1. Scenarios assuming single engineered barrier failure immediately upon repository closure and the impact of this event on the performance of other barriers

Impact on EBS	EBS 7	EBS 6	EBS 5	EBS 4	EBS 3	EBS 2	EBS 1
EBS 7	–	Increased groundwater flows. Risks of intense siltation	–	Impact of seepage and vadose water	–	–	–
EBS 6	Increased seepage	–	–	Impact of seepage and vadose water	–	–	–
EBS 5	–	Decreased water volume	–	–	Accelerated degradation	–	–
EBS 4	–	–	–	–	Accelerated degradation	–	–
EBS 3	–	–	Integrity loss, subsidence	Integrity loss along the walls	–	Accelerated degradation	–
EBS 2	–	–	–	–	–	–	Accelerated degradation
EBS 1	–	–	–	–	–	Impact of corrosion products (for example, ZhZK)	–

the vadose zone (if any) and the surface water seepage zone;

- drainage structures fail (EBS 6): water seepage into the cement-soil wall gets more intense, the underlying clay cap enters the vadose water zone (if any) and the surface water seepage zone;
- covering cap fails (EBS 5): seepage water inflow into the drainage system decreases, concrete structures of walls, bottom and roofs ingress seepage water, which leads to their accelerated degradation and destruction;
- clay cap fails (EBS 4): early wetting and degradation of all concrete structures;
- concrete structures constituting to repository walls, bottom and roof fail (EBS 3): the covering cap loses its stability, the integrity along the walls gets lost, degradation of the buffer material occurs;
- buffer material fails (EBS 2): accelerated degradation and destruction of RW containers.

2. Further, scenarios assuming simultaneous failure of two EBS immediately upon repository closure and the impact produced by this event on the other barriers were considered (Table 2).

The first group of combinations with 7 double elements in threes (35 in total) was calculated and the realistic ones were identified (in accordance with the diagram shown in Figure 7).

In accordance with Table 2, failure of the following EBS elements is expected to impact the system in the following way:

- EBS 7 and EBS 1: increased groundwater inflow to the drainage system, which may cause early siltation, the underlying clay cap enters the vadose water zone (if any) and the surface water seepage zone;
- EBS 6 and EBS 2: increased level of water seepage into the cement-soil wall and through the underlying clay cap triggering accelerated degradation and destruction of RW containers;
- EBS 5 and EBS 3: decreased water inflow to the drainage structures resulting in the failure of repository walls, accelerated degradation of concrete structures and buffer material.

Further EBS combinations are similar to the previous ones.

The second group of combinations with 7 double elements in threes each (35 in total) is calculated with the realistic ones being identified (in accordance with the diagram shown in Figure 7 and Table 3, which was built by rearranging the right column of Table 2 up by one element).

In accordance with Table 3 upon:

- EBS 7 and EBS 2 failure, the volume of groundwater in the drainage system increases causing early silting, the underlying clay cap enters the vadose water and surface water seepage zone which accelerates the rate of RW container degradation and destruction,
- EBS 6 and EBS 3 failure, water seepage into the cement-soil wall and the underlying clay cap gets more intense, the covering cap loses its support, the integrity along the walls is lost,
- EBS 5 and EBS 4 failure, water flow to drainage structures gets less intense, walls lose their integrity, degradation of concrete structures occurs faster.

Table 2. Scenarios assuming the failure of two EBS elements immediately upon repository closure and the impact of this event on other barriers and their performance (Group 1)

Impact on EBS Failure	EBS 7	EBS 6	EBS 5	EBS 4	EBS 3	EBS 2	EBS 1	Failure
EBS 7	–	Increased groundwater flows. Risk of intense siltation	–	Impact of seepage and vadose water	-	-	-	EBS 1
EBS 6	Increased seepage	–	-	Impact of seepage and vadose water	-	-	-	EBS 2
EBS 5	–	Decreased water volume	-	Integrity loss along the walls	Accelerated degradation	Accelerated degradation	-	EBS 3
EBS 4	–	–	-	-	Accelerated degradation	-	-	EBS 4
EBS 3	–	Decreased water volume	-	Integrity loss along the walls	Accelerated degradation	Accelerated degradation	-	EBS 5
EBS 2	Increased seepage	–	-	Accelerated water saturation	-	-	Accelerated degradation	EBS 6
EBS 1	–	–	-	-	-	Corrosion product impact (for ex., RCS)	-	EBS 7

Table 3. Scenarios assuming failure of two EBS immediately upon repository closure and the impact of this event on other barriers and their performance (Group 2)

Impact on EBS / Failure	EBS 7	EBS 6	EBS 5	EBS 4	EBS 3	EBS 2	EBS 1	Failure
EBS 7	–	Increased groundwater flow. Risk of intense siltation	–	Impact of seepage and vadose water	–	–	–	EBS 2
EBS 6	Increased seepage	–	–	Impact of seepage and vadose water	–	–	–	EBS 3
EBS 5	–	Decreased water volume	–	Integrity loss along the walls	Accelerated degradation	–	–	EBS 4
EBS 4	–	–	–	–	Accelerated degradation	–	–	EBS 5
EBS 3	–	–	–	Integrity loss along the walls	–	–	–	EBS 6
EBS 2	–	–	–	Accelerated water saturation	Accelerated degradation	–	–	EBS 7
EBS 1	–	–	–	–	–	Corrosion product impact (for ex., ZhZK)	–	EBS 1

Further EBS combinations are similar to the previous ones.

The following tables were built similarly to Tables 2 and 3 with the events in the right column permuted up by one element. The total number of combination groups with 7 double elements in threes was equal to 7 (7 tables) with 21 combinations corresponding to the diagram shown in Figure 7.

At the next stage, the number of combination groups with 7 triple elements in fours was analyzed. At the same time, right column was added to Table 2 with an upward shift of one event (for example, EBS 7, EBS 1 and EBS 2 — first group). Combination options were continuously considered with relevant sweeping of the groups.

EBS failure scenarios studied in various combinations showed that the most dangerous scenario with the largest number of barriers involved in the degradation process (EBS 5 and EBS 3), is the covering cap and concrete structure (walls, bottom, roof slabs) failure. Therefore, to enhance the long-term disposal safety, one should address the issues providing a longer service life for these elements.

3. A scenario was considered taking into account the internal degradation processes occurring in the containers with radioactive waste (EBS 1) triggered by moisture ingress, biological substances and bacteria (Figure 8).

Early EBS 1 failure (after 50 years) is an internal process affecting subsequent degradation stages from the inside of EBS 2 with its buffer material failure (clay or bentonite backfill) expected to occur in 300—500 years. EBS 5 and EBS 3 are expected to get affected by external factors in 400—600 years. Given the adopted safety barrier failure sequence, degradation processes occurring inside the EBS 1

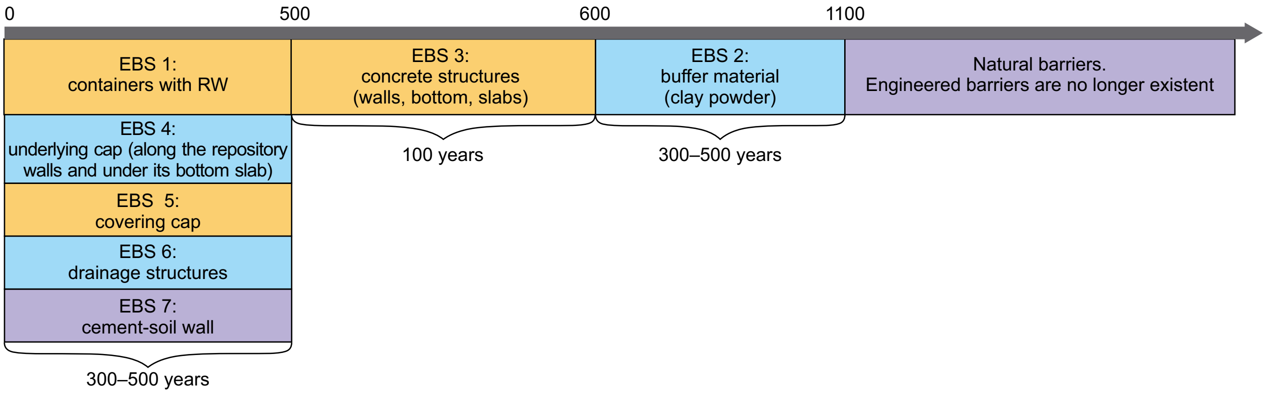


Figure 8. Scenario considering internal degradation processes triggered by moisture, biological substances and bacteria in the RW containers (EBS 1)

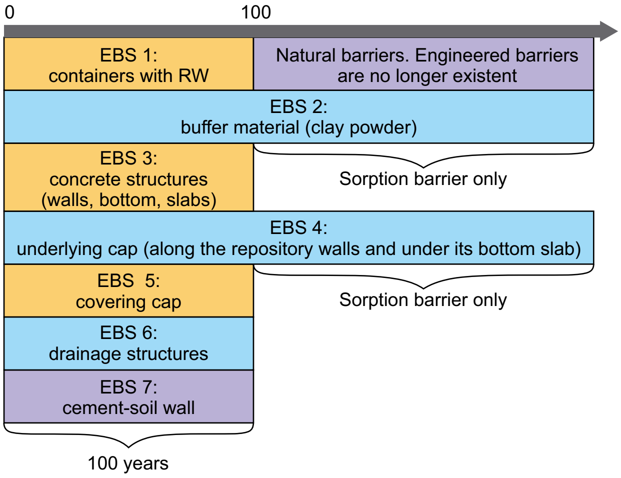


Figure 9. Diagram showing simultaneous commissioning of engineered safety barriers in time. Most conservative scenario

containers and the EBS 2 buffer material induce certain conditions that may result in an early external impact on radionuclides, therefore, initiating their release outside the repository 300–500 years earlier.

Similarly, scenarios considering early failure of other EBS due to various influences are considered in a time sequence: the influence of pore, surface and ground waters, etc. in the resulting barrier combinations.

4. The most conservative scenario: all EBS start their operation immediately after the repository is filled with RW containers (the repository is closed) (Figure 9).

EBS 3, involving concrete and metal structures, may resist degradation processes effectively for a time period of 100 years, upon the expiration of which EBS 3 may start to collapse. Since the walls and the bottom slabs were acting as a support for EBS 5, the covering cap may fail earlier than expected according to the designs.

EBS 4 and EBS 2 provide the highest resistance to groundwater flows with the waterproofing capacity and anti-migration properties inherent to clay and bentonite. For this reason, under this scenario, the RW containers can provide effective isolation for a time period of 300—500 years.

Figure 9 demonstrates that even under a conservative scenario, the transition to the application of high-strength concrete in EBS 3 structures, EBS 6 drainage systems and the soil-cement wall EBS 7 may provide long-term isolation of RW for at least 300 years, whereas, barriers based on natural clays can provide disposal safety for up to 500 years.

It is important to take this consideration into account when calculating the activity of radionuclides released from the repository into the environment. Over an additional 500 years, their hazard level is expected to decrease due to the radioactive decay process.

Conclusion

The paper considers a system of engineered safety barriers and its operation within the structure of near-surface disposal facilities for radioactive waste. Currently, in accordance with NP-055-14 provisions, RW disposal safety in near-surface repositories is provided by a system of engineered safety barriers consisting of the following elements:

1) metal or reinforced concrete containers providing RW containment for at least 30—50 years and up to 300 years, respectively;

2) buffer material based on natural clays used to backfill the gaps in the compartments and between the RW containers; the containment capacity may be provided for at least 300—500 years;

3) concrete structures of walls, bottom and upper repository slabs installed in accordance with the accepted GOSTs; service life of concrete structures amounts to 100 years;

4) clay cap and bentonite mats installed along the perimeter (walls, bottom) of the disposal facilities; barrier service life amounts to at least 300—500 years;

5) covering waterproofing cap involving the following elements (from the bottom to the top): a clay waterproofing cap, a drainage layer made of a gravel-sand mixture, protective crushed stone layer, protective layer of loam and a soil-vegetation layer. The covering waterproofing cap of the repository is designed to retain the intended properties for at least 300—500 years.

Some additional engineered barriers may be introduced into repository designs to increase its long-term safety period:

6) drainage system — an engineered structure draining surface and groundwater from the repository, which is arranged in accordance with the specific repository siting conditions taking into account the atmospheric precipitation seepage and the vadose water level;

7) sheet piling and cement-soil walls installed around modular repository structures both during repository construction, operation, as well as around already closed disposal facilities (backup).

To increase the long-term safety of EBS 3 structures, one should switch to the use of concrete commonly applied in the production of RW containers (NZK-150-1.5P containers). If class B50 concrete (M700, GOST 26633-91) with a compressive strength of 70 MPa, a density of 2.45 to 2.65 t/m^3 and a frost resistance and water resistance grade of at least F200 and W12 is applied, EBS 3 service life may amount to up to 300 years. All other safety barriers constituting to the disposal system may provide the long-term safety for at least 300 years.

The combinatorics method was used to identify most risky scenarios assuming failure of a maximum number of engineered safety barriers, namely, EBS 3 and EBS 5, i. e., failure of concrete structures (walls, bottom, roof slabs) and covering cap. To extend the long-term safety period provided by near-surface disposal facilities, one should somehow extend the EBS 3 and EBS 5 operation period; therefore, one should switch to use of EBS 3 made of high-strength concretes. According to the adopted failure sequence flowchart proposed for the safety barriers, degradation processes occurring inside the EBS 1 containers and EBS 2 buffer material are expected to result in an early external impact on radionuclides, therefore, initiating their release outside the repository 300—500 years earlier.

The system of engineered safety barriers provides reliable long-term containment, prevents the spread of ionizing radiation and radioactive substances from the repository to the environment.

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