PRELIMINARY ASSESSMENT OF ENGINEERED BARRIER PARAMETERS UNDER DGR CONCEPT WITH HORIZONTAL ORIENTATION OF RW PACKAGES IN COPPER COATED CONTAINERS

Bogatov S. A.[1], Drobyishevskiy N. I.[1], Krupskaya V. V.[2,3], Zakusin S. V.[2,3], Lekhov V. A.[3]

[1]Nuclear Safety Institute of the Russian Academy of Sciences, Moscow, Russia

[2]Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of the Russian Academy of Sciences, Moscow, Russia

[3]Lomonosov Moscow State University, Moscow, Russia

Article received on December 22, 2022

The paper discusses a DGR concept providing for heat-generating radioactive waste (RW) disposal in relatively thin-walled steel containers with a copper coating in packages of compacted bentonite blocks installed into horizontal drifts. The study assumes that this DGR layout should provide safe disposal of historical RW Class 1 with relatively low activity and heat generation levels. The proposed concept imposes appropriate restrictions on the bentonite buffer, among which the paper quantitatively considers the thickness varying depending on the residual RW heat release, the minimum dry density, as well as the content and type of montmorillonite. For further assessment purposes, the paper proposes to consider bentonite blocks made of compacted bentonite from Russian deposits with a predominant content of sodium montmorillonite characterized with minimum required dry density. The authors also proposed to fill the gaps between RW packages made of compacted bentonite and drifts with pellets. Such bentonite pellets should have maximum achievable dry density and a predominant content of calcium montmorillonite.

Keywords: *radioactive waste, clay materials, nuclear legacy facilities, RW disposal, engineered barriers.*

Introduction

At present time, scientific research is run to demonstrate the feasibility of deep geological (DGR) and some alternative concepts proposed for radioactive waste (RW) Class 1 and 2 disposal. In particular, studies performed in line with an adopted strategy are focused on the crystalline rock massif at the Yeniseiskiy site (Krasnoyarsk Territory) [1], [2]. Thus, previously approved design options [3] are being evaluated considering possible trends for their further adjustment (see, for example, [4]—[7]). This paper also evaluates possible design solutions and the required properties of engineered barrier materials under the so-called “horizontal” concept, i. e., when the waste containers with RW Class 1 (RW-1) are disposed of in several tiers into horizontal drifts with buffer blocks made of compacted bentonite (CB). This practice is most widely considered under Canadian DGR designs for spent nuclear fuel (SNF) from CANDU reactors (Figure 1 [8]), but is also discussed in Russia [6], [7].

The aspects discussed below support the application of this concept under Russian DGR designs.

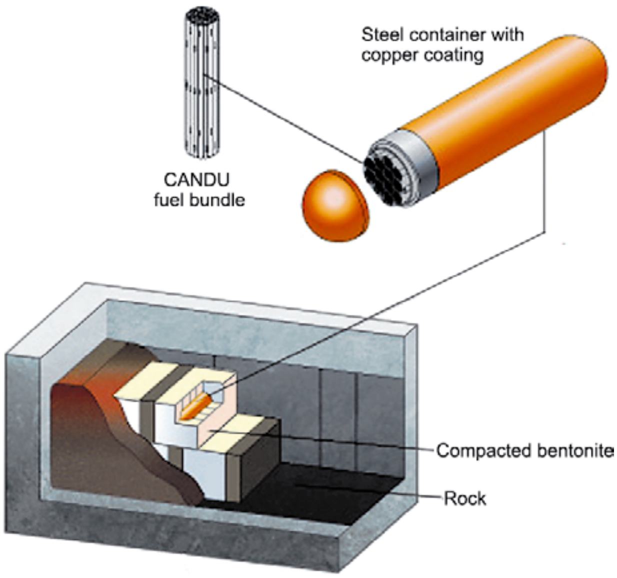

Figure 1. Concept proposed for SNF from CANDU reactors providing its disposal in horizontal drifts [8]

Firstly, recent estimates showed that the activity and heat release from vitrified historical high-level waste (VHLW) inventory stored at the PA Mayak site [9] turned out to be much lower than the expected levels provided for under the DGR designs developed for the Yeniseiskiy site [3]. Secondly, the maturity level of methods providing the application of protective copper coatings to disposal steel containers [10] has grown considerably and they are being mastered in Russia [11]. Therefore, lighter container designs that may considerably facilitate RW management operations at the transportation and disposal stages can be now considered as an alternative to the existing ones. For example, to manage a relatively light container and a package with relatively low activity waste either a forklift with radiation protection designs securing the operator can be used or relevant requirements can be lowered down similar to the weight, size and lifting characteristics of remote equipment designed to move the packages, to install the buffer material and to backfill the DGR excavations. Given the latter aspect, one may consider the horizontal disposal concept as a possible alternative to the borehole one with horizontal drifts alone used for RW disposal purposes. Thus, DGR designs proposed for the Yeniseiskiy site provide for two-tier RW disposal in 54 horizontal drifts covering an area of approximately 300 × 700 m; 14 drifts were set aside for historical RW-1 considered as a priority waste stream for disposal.

The study evaluates the prospects of this concept application under the DGR designs developed for the Yeniseiskiy site and outlines further needs as regards EBS design optimization.

1. Container and design options

1.1. Shell thickness

Open drums made of 4-mm-thick carbon steel with an outer diameter of 0.575 m and a capacity of 0.2 m3 are used at PA Mayak as a primary packaging for VHLW subject to priority disposal in the DGR. Their overall height accounts for 1 m. At the storage stage, drums are grouped by 3 pcs. into steel cases [12].

The paper [13] discussing the requirements applicable to RW-1 packages intended for deep geological disposal states that the container shell should be able to provide a mechanical compressive strength of at least 10 MPa and remain tightly sealed for a period of at least 1,000 years. [14] presents the approaches applied to calculate the shell thickness of a steel container intended for RW-1 disposal in a CB buffer. Based on these approaches, to withstand an isostatic load of 10 MPa, the thickness of a carbon steel container shell (excluding the corrosion allowance) should be not less than 27 mm, whereas its flat lid should be not less than 70 mm thick.

A few factors may contribute to steel container degradation, namely, of its copper coating, including sulfide concentration in groundwater, sulfate-reducing bacteria and their vital activity, certain bentonite buffer parameters, the surface dose rate, etc. Although, current stage of research provides no opportunities for a fully-fledged analysis that would cover all factors responsible for copper coating corrosion under the Yeniseiskiy site's disposal conditions, the latest findings look quite optimistic. For example, even under most conservative assumptions, copper coating corrosion in the Canadian rock massif is not expected to exceed 1.2 mm over a 1-million-year time period, whereas assuming some realistic parameters it was estimated at a level of 270 μm [15].

Given the above, further assessments of container designs intended for VHLW drum emplacement considered a wall thickness of 5 cm with the upper 5 mm constituting to a copper coating[1]. The resulting container diameter of 70 cm basically suggests that available infrastructure may be used to handle the RW packages directly at the PA Mayak site [16].

The adopted container thickness should also account for asymmetric loads produced by bentonite swelling and have sufficient rigidity to maintain integrity under shear loads caused by rock displacements triggered by seismic impacts (see section 2.2.

[1] The Canadian concept considers a copper coating thickness of 3 mm Cu sufficient for a steel container [8]. It was also adopted based on a requirement stating that the dose rate on its surface should not exceed 1 Gy/h [14].

Maximum dry density of compacted bentonite blocks). These processes deserve appropriate numerical evaluation under further studies.

1.2. Containers spacing based on heat release criteria

Temperature of bentonite material interacting with the waste container was considered first as a criterion that would affect the DGR layout given a horizontal disposal concept. It was believed that the maximum temperature should not exceed[1] 100 °C. Heat release expected from the RW-1 at the time of its disposal was taken into account [9] with the characteristic thermal conductivity and heat capacity of non-water-saturated bentonite assumed as being equal to 0.96 W/(m·K) and 1,150 J/(kg·K), respectively. Figure 1 presents the proposed waste container layout. According to conservative (with no account taken of waste disposal dynamics and bentonite saturation with water) estimates, the distance between the axes of adjacent containers with three VHLW drums in each amounted[2] to approximately 1.5 m, with two drums — to about 1 m. Since the pre-disposal stage provides for HLW container in-situ packaging into a CB layer with blocks of various shapes given the adopted assumptions, the planned dimensions and weight of the resulting packages would amount to 1.5 × 1.5 × 4 .5 m and 22 t in case if 3 drums were supposed to be emplaced into a single container and 1.5 × 1.5 × 3.5 m and about 18 t if 2 drums were provided for in the designs. Figure 2 presents a VHLW disposal layout assuming two drums placed into a single container.

1.3. Management of RW packages in the DGR

Container designs suggesting that two drums are emplaced into a single package seem to be more advantageous since a commercial forklift, for example, a diesel forklift TCM FD230-2 with a lifting capacity of 23 tons (L × W × H = 7,990 × 3,060 × 3,580) can be used for its transportation purposes [17]. Its capacity is enough to install some radiation protection to secure the operator. Preliminary estimates in the MicroShield v.9.05 software showed that a 15 cm-thick shielding made of "heavy" (high in lead) glass installed between the package and the

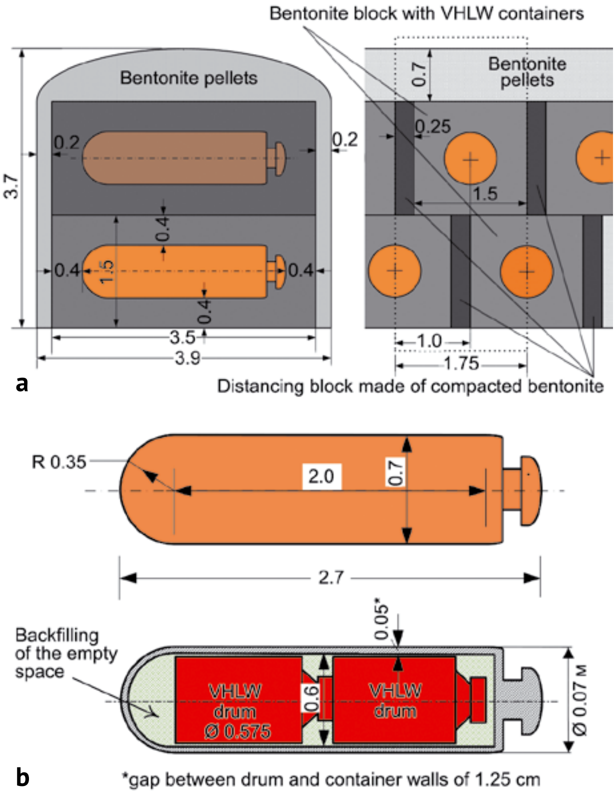

Figure 2. RW-1 package layout proposed under the horizontal disposal concept: a) cross-section and longitudinal section of a drift; b) container with VHLW drums (dimensions are given in meters)

forklift operator would reduce the dose rate at the operator's workplace to about 13 μSv/h, which corresponds approximately to the OSPORB-99/2010 standard [18] set forth for temporary premises intended for A group personnel (12 μSv/h given 850 working hours per year).

It should be noted that these estimates provide only some preliminary data on the radiation characteristics of waste packages and do not account for the dose rate increase observed when the operator approaches a RW package stack and should be clarified at further research stages. Remote lifting devices are used in case if the radiation safety cannot be provided at the operator's workplace: containers are moved in additional packaging, as, for example, provided in [8].

2. Buffer made of compacted bentonite blocks designed for a RW-1 container

In crystalline rocks, a CB buffer[3] is responsible for the following basic safety functions (SF) [19]:
- to protect the RW packaging against the effects produced by hazardous events and processes

[1] This criterion taken by analogy from concepts proposed abroad should be considered as quite conservative and, perhaps, can be increased by 10–20 °C with no decrease in the DGR safety.

[2] The indicated spacing between the container axes were calculated assuming that the minimum thickness of the buffer should be 40 cm and the distance between the axes of adjacent excavations should account for approximately 15 m. Relevant explanations on the selected parameters are given below, but, similarly to many other cases, they were taken only for preliminary estimates and deserve further optimization.

[3] A buffer is an engineered barrier surrounding a RW container and filling the gaps between the container and the rock.

(including hydraulic, mechanical, chemical and microbiological) that may jeopardize its SF, i. e., containment of radioactive substances;
- to limit and delay the release of radionuclides in case of RW package failure;
- to provide and maintain favorable mechanical, geochemical and hydrogeological conditions specified for the RW packages.

In turn, the basic SF form a basis for a multi-level system of requirements and quantitative safety indicators that should be developed under the DGR designs. Development of a fully-fledged system will be discussed in further papers; whereas, this article mentions only few of them that may be used to estimate the buffer parameters under the preliminary safety assessments of the horizontal DGR concept, namely its composition and density.

The estimated minimum bentonite density and the associated swelling pressure and water permeability depend on a few factors; the basic ones are: mechanical strength at the stage of CB handling in the DGR, erosion compensation at the buffer saturation stage, prevention of RW container subsidence and displacements, inadmissibility of radionuclide transport with colloids, suppression of microbial vital activity and prevention of chemical releases from the outside that may considerably accelerate container corrosion. The maximum bentonite density can be calculated based on a compromise between its barrier properties, container strength, i. e., its resistance to mechanical loads associated with the swelling pressure produced by bentonite (P_s), and the minimum required ductility to prevent container failure under the loads expected due to host rock (HR) block displacements.

Under further illustrative assessments, the barrier properties of bentonites were assumed to be governed by the dry density (matrix density) of montmorillonite contained in it, which, given the nature of the predominant exchangeable cations (Ca or Na), are called Ca-montmorillonite and Na-montmorillonite (Ca-MM and Na-MM). The CB swelling pressure can be measured in the cells of a constant volume, as given in [22]. Bentonite from the 10th Khutor deposit, Republic of Khakassia (10X) and Tagansk deposit, Republic of Kazakhstan (T) were considered in the study as potentially suitable DGR buffer materials. Both bentonites contain approximately 70 % of montmorillonite (MM), with Ca-MM predominating in the 10X material and Na-MM — in the T one. To a first approximation, one may assume identical dry densities for MM and other bentonite components. Figure 3 presents the swelling pressure and their exponential approximation from the dry MM density measured in the 10X and T bentonites and model groundwater from

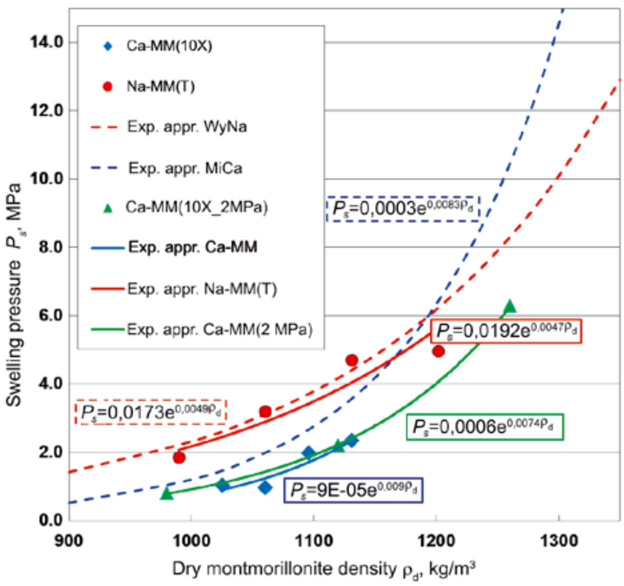

Figure 3. Swelling pressures and their approximation depending on the dry montmorillonite density (water mineralization level is similar to the one expected at the Yeniseiskiy site) obtained from the experiments

the Yeniseiskiy site, as well as given water mineralization level of 0.1 M (NaCl) based on data from [20] and [21].

The graphs demonstrate the accuracy of earlier assumptions. It should be noted that the approximations from [21] were obtained from a larger number of points, in a wider range of densities and are considered more reliable.

Dry MM density was considered specifically to extrapolate the findings from similar studies to the unknown parameters of Russian bentonites. Further studies will be focused on 10X, T bentonites and a mixture of 10X with kaolin clay KK in a weight ratio of 30 : 70 (wt.) — B30KK70.

2.1. Minimum dry density of compacted bentonite blocks and gap filling pellets

2.1.1. Swelling pressure

Quite simple assumptions underlie the minimum swelling pressure selected for bentonite: first of all, it and other bentonite characteristics associated with it should provide the predominance of contaminant transport by diffusion over the advective one, make up for buffer erosion at the saturation stage and prevent microbial activity and colloid transport through the buffer.

The latter two requirements (with a margin for conservatism) are met at a swelling pressure of over 2 MPa (see, for example, [23]—[25]), which corresponds to MM densities of 1...1.1 g /cm^3 in the dry state (Figure 3). However, one should also account for the gaps between the CB and the excavation walls filled with pellets having much lower bulk density than the CB layer. The maximum (bulk) pellet density in a dry state depends on the currently unavailable void space backfilling methods. Under current illustrative estimates, the dry bulk density of the pellet layer was assumed as equal to 1.2 g/cm^3 (or $\rho_{MM\text{-}P} = 1.2{\cdot}0.7 = 0.84$ g/cm^3 — MM for bentonites of 10X and T type). Given the ratio of volumes filled with blocks/segments, the CB (with no account taken of the container volume) and pellet ratio would be equal to approximately 0.71 : 0.29, whereas the MM dry density in blocks ($\rho_{MM\text{-}P}$, g/cm^3) can be calculated based on the below relation:

$$0{,}71\ \rho_{MM\text{-}P} + 0{,}29{\cdot}0{,}84 = 1\ldots1{,}1\ [\text{g/cm}^3\}. \quad (1)$$

Thus, effective dry density according to Ca-MM 1.1 g/cm^3 can be achieved at $\rho_{MM\text{-}P}$ equal to 1.21 g/cm^3 (given a 10X bentonite density of 1.21/0.7 = 1.73 g/cm^3), whereas if taken according to Na-MM 1 g/cm^3 it should be equal to 1.07 g/cm^3 (given T bentonite density of 1.07/0.7 = 1.53 g/cm^3). For a barrier material made from a mixture of 10X and T bentonites, the minimum dry density was estimated as falling into a range of 1.53—1.73 g/cm^3.

In case of B30KK70, which is a bentonite (B) and kaolin clay (KK) mixture with MM content ranging from 0.3·70 % (10X) + 0.7·15 % (KK) ≈ 32 % (recalculated based on MM concentrations) and up to 36 % (direct measurement in [26]), the block density according to Ca-MM estimated as being equal to 1.21 g/cm^3 should correspond to a mixture density, i. e., 1.21/(0.36…0.32) = 3.36…3.78 g/cm^3. However, this value appears to be higher than the particle density of minerals contained in the clay material and the technical performance of methods involved in compacted block production. Production methods mastered to date provide the fabrication of bentonite blocks with characteristic dimensions of about a meter and a dry density of up to 1.7…1.8 g/cm^3, as well as cylindrical prototypes of up to ~ 10 cm and a dry density of up to 2.0 …2.1 g/cm^3. Higher dry density levels would require a compaction pressure of over 150 MPa [27], [28].

Kaolin-bentonite mixtures were not considered further in this paper due to difficulties expected in achieving the required density.

The diffusion mechanism standing behind the contaminant transport through bentonite buffer is governed by the following condition (see, for example, [29]):

$$\mathrm{Pe} = \frac{KiL}{D_e} < 1\,, \quad (2)$$

where Pe is the Peclet number; K is the permeability coefficient for bentonite; i is the hydraulic pressure gradient; L is the buffer thickness; D_e is the effective diffusion coefficient. The above condition is hard to meet even in case of 10X pellets with a dry density of about 1 g/cm^3, a buffer layer thickness L = 0.2 m, permeability coefficient $K \approx 10^{-11}$ m/s [30], effective diffusion coefficient $D_e \approx 10^{-10}\ldots10^{-11}$ m/s and $i \approx 0.05$, $\mathrm{Pe} \approx 10^{-2}\ldots10^{-3} << 1$, i. e., there's a large margin for the diffusive transport condition to be met.

2.1.2. Mechanical buffer erosion at the saturation stage

Erosion and channeling may evolve along with buffer material saturation with water, especially at early stages upon excavation closure. Macroparticles of the material may get washed out along the way resulting in lower buffer density (Figure 4).

In crystalline rocks, excavations tend to get saturated basically through several large fractures intersecting the excavations. Depending on the inflow rate, water from the fracture would either manage to get absorbed by the buffer or flow further contributing to channel formation. Partial water absorption and buffer swelling is expected to result in bentonite gel formation at the channel walls contributing to more intensive material particle

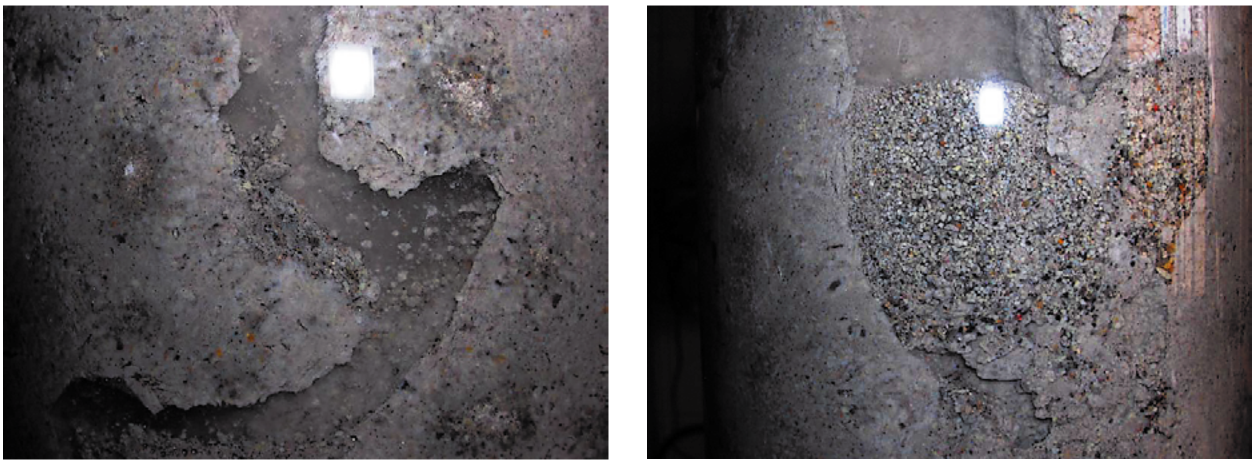

Figure 4. Characteristic channels and cavities formed in bentonite at the early stage of its saturation with water [32]

leaching. Over time, along with further bentonite saturation and swelling, buffer material leaching becomes less intense [31]—[33]. This process depends on numerous factors that are too difficult to consider comprehensively at the current stage of research. Thus, an empirical approach is used. For example, [34] calculates the eroded bentonite mass considering an excavation area intersected by a fracture, m_s, based on the water volume that passed though it, V_w, and the average bentonite concentration in it, cs:

$$m_s = c_s V_w{}^n, \tag{3}$$

where $n = 0.65\ldots1$ is an empirical coefficient. V_w, as a first approximation, depends on the volume of voids present in the buffer backfill (pore volume in blocks and pellets was not taken into account), which is associated with the gaps between bentonite blocks, containers and the excavation walls backfilled with pellets. Assuming a dry bulk pellet density of 1.2 g/cm^3 and their structure formed by compacted bentonite with a density of 1.7 g/cm^3, one may easily calculate the gap volume, which would account for about 30 % of the volume backfilled with pellets.

Most intense buffer erosion would be prompted by a water-conducting fracture intersecting the excavation vertically. The volume of material that can be eroded from an excavation by a water flow can be roughly calculated based on [35]. Studies showed that under DGR conditions the flow within a permeable object would be concentrated in its volume adjacent to the fracture with a width accounting for ~ 10 % of its maximum characteristic size. In our case, a permeable "object" can be understood as the characteristic length of an excavation between large water-conducting fractures intersecting it. For illustrative purposes, one may assume, for example, that the water inflow into a 300 m long excavation is driven by four large water-conducting fractures; the size of the "object" accounts for 300/4 = 75 m; the length of the eroded excavation volume (where the flow from the fracture is concentrated) accounts for 7.5 m. In accordance with the accepted geometry of the excavation (Figure 2), the empty space volume in the under-roof gap between the blocks and the excavation at a length of 75 m would be equal to some 80 m^3. Given the gaps left during CB and container installation, this volume may be added by 10 m^3 and one may assume a V_w of 90 m^3.

According to medium-scale laboratory experiments [31], early in the backfill erosion process the cs peaked to 20 g/L and then dropped to a relatively constant level of 2 g/L. The average cs level should be calculated based on a convolution of time dependent flows causing erosion and concentrations. Nevertheless, under preliminary assessments, the average cs was taken equal[1] to 3 g/l. The leached bentonite mass ms amounted to 3·90,000 = 270 kg. The total bentonite mass that constituted to the backfill within the leached excavation section of 7.5 m would amount to approximately 141.2 tons assuming its dry density of 1.7 g/cm^3, whereas the portion of leached bentonite (before its complete saturation) would amount to about 0.2 %, i. e., appears to be quite negligible.

2.1.3. Micro-erosion of bentonite

At the early buffer saturation stage, erosion is prompted by the separation of relatively large bentonite particles (aggregates) by high-pressure groundwater (GW) flows: this mechanism can be conventionally called macro-erosion. If the saturated bentonite has a free boundary, for example, at the interface with a water-conducting fracture, its swelling causes gel formation (area of coupled particles), which, under certain conditions, can expand further and turn into a colloidal particle solution that can be carried away by a GW flow. This mechanism can be conditionally called micro-erosion.

Under ideal conditions, CB swelling in an excavation would be limited by its walls, which, in fact, contributes to swelling pressure buildup. However, in case of some fractures crossing the excavation, expansion and penetration of bentonite into them would decrease its density in the excavation and deteriorate the barrier properties. In terms of its extent, this process is governed by numerous parameters, but in case of GW with low mineralization level and the predominance of monovalent sodium ions in montmorillonite, bentonite is expected to swell freely for quite a long time. The boundary layer of bentonite at its interface with the GW is first transformed into a viscous gel, which, along with its further expansion and density decrease, turns into a colloidal particle solution that can be carried away by GW flow far beyond the excavation. In case of high (over ~ 20 % (mass)) content of Ca-MM in the MM or GW mineralization of over[2] 4 mM, this process won't evolve — the gel formed at the bentonite–GW interface would remain stable enough to prevent further erosion [47].

In terms of microerosion, the flow rate of GW interacting with the bentonite surface is seen as a crucial parameter. The GW rate in the excavation

---

[1] Findings from the Scandinavian experiments should be extrapolated to the Russian case with caution, since cs depends strongly on the groundwater mineralization level, which is most likely expected to be much lower in the Russian massif.

[2] According to [48], GW mineralization level at the Yeniseiskiy site accounts for approximately 3.2 mM NaCl.

damaged zone is evaluated below assuming the considered concept.

Three key processes are responsible for the resulting excavation damaged zone (EDZ): the redistribution of existing stresses, their displacements in the excavations (ZSP_{SSS}) and shock wave pressure during drilling and blasting operations (EDZ_{DBO}). It's not always possible to specify the damage induced by an individual mechanism. According to [42], the characteristic size of an EDZ, the permeability coefficient in which grows by 2—3 orders of magnitude along the excavation axis (but decreases by about 5 times in the radial direction), can reach 1.5 m for a standard borehole excavated by the drilling and blasting method. [43] overviews the characteristic EDZ parameters from European, Canadian and Japanese studies. At the DBO stage, the depth of EDZ_{DBO} propagation amounts to several tens of centimeters: usually about 30 cm on the sides and in the roof and approximately 80 cm at the bottom of the excavation. The permeability coefficient decreases with depth averaging about 10—10 m/s. However, in rocks with large tectonic or heat-induced stresses in the vicinity of HLW containers, the EDZ_{SSS} permeability coefficient may reach 10^{-6} m/s and propagate to a depth of about 20 cm due to rock spalling observed along the walls. To a large extent, these parameters would depend on the excavations, namely, on their orientation relative to the axes of the main stresses (the most favorable case assumes their orientation along the greatest stress axis). In case of any "distortions" in the excavation orientations, the EDZ_{SSS} may grow in a quite considerable way.

Thus, in terms of its transport properties, EDZ would be considerably affected by rock spalling processes evolving on the excavation walls. In [44], a basic permeability coefficient[1] of 10^{-8} m²/s was assumed for an EDZ with a porosity of 2 %; variant calculations assumed its increase to 10^{-6} m²/s.

Under further illustrative estimates, the EDZ depth was assumed as being equal to 0.5 m; porosity — 3 %; permeability coefficient — $2{\cdot}10^{-8}$ m/s.

Increased GW flow rate, *f*, in the EDZ compared to the undisturbed rock can be roughly estimated based on data from [45] providing a solution for a two-dimensional problem. If the characteristic size of an increased permeability zone (IPZ) with a permeability coefficient K_{in} is equal to b and the longitudinal (along the GW flow) and the undisturbed rock permeability coefficients are assumed as a and K_{out}, respectively, then:

$$f = \frac{\alpha(\beta+1)}{\beta+\alpha}, \text{ where } \alpha = \frac{K_{\text{in}}}{K_{\text{out}}} \text{ and } \beta = \frac{a}{b}. \quad (4)$$

If the excavation length a is assumed as equal to 300 m and the EDZ depth $b = 0.5$ m, then $\beta = 600$. The permeability coefficient characteristic of the undisturbed rocks at the Yeniseiskiy site (K_{out}) assuming some moderate requirements for acceptance criteria amounts to $10^{-10}...10^{-9}$ m/s [46] and $K_{in} = 2{\cdot}10^{-8}$ m/s, $\alpha = 20 ...200$. Thus, f may vary within a range of 19...150. This estimate can only be considered approximate, but it seems clear that given realistic data on the permeability of IPZ and rock and the excavation geometry, the flow rate in it is expected to grow by 1—2 orders of magnitude with the flow rates in the undisturbed rock of ~ 10 m/year [46].

Quantitative calculations of Na-bentonite erosion rate are quite complex, may be implemented solely based on appropriate numerical methods and still remain a subject of ongoing research (see, for example, [49]). However, based on available conservative estimates of Na-MM erosion in a fracture with the GW rate corresponding to the one expected in the IPZ at the Yeniseiskiy site (i. e., over 100 m/year), one was able to calculate the value for an excavation with its dimensions similar to the considered ones, which amounted to about 200 g/year [50]. Even though no account was given to the frictional forces acting on the crack surfaces, inert contaminants found in bentonite and contributing to protective layer formation during its partial erosion, etc., the use of eroded bentonite on the excavation periphery is still considered problematic. For example, given earlier assumptions, estimates focused on bentonite erosion at the saturation stage (about 140 tons in the eroded area) showed that such a loss rate would result in about 20 tons of bentonite washed out over 100,000 years. Thereby, its density would turn out to be insufficient to perform its barrier functions, namely, those related to the swelling pressure (see section 2.1.1. Swelling pressure).

2.2. Maximum dry density of compacted bentonite blocks

The maximum bentonite density mainly depends on a balance maintained between the container strength and the plastic buffer deformation contributing to container integrity in case of shear rock displacement that may occur along the planes of a fracture crossing the excavation and driven by seismic impacts. The loads acting on the buffer-container system are closely related to the rock acceptance criteria, which are seen as a compromise between the desire to excavate the DGR boreholes

[1] Permeability T is related to the permeability coefficient K as $T = K{\cdot}d$, where d is the thickness of the rock layer with the permeability coefficient K.

in most durable and intact rocks and using the mining allotment capacity to the fullest extent possible. Apparently, this concept may be approved for the Yeniseiskiy site only based on some positive feedback from the field studies of rocks constituting to the target disposal horizon preceded by shaft excavation efforts. As a first approximation, one may consider the design option adopted by the Finnish company Posiva Oy, i. e., a container surrounded by a bentonite buffer should remain intact under a shear rock displacement of 5 cm at a rate of 1 m/s [36], [37].

Quantitative requirements to the buffer-container system may be established only considering some specific container and buffer design options. RW packages proposed under the considered concept are much inferior to the Scandinavian designs (a cast iron Ø949 insert for SNF assemblies in a 5-cm-thick copper shell) in terms of their strength and rigidity [38]. To make up for the lower container strength and rigidity assumed under the former concept, buffer thickness and/or its plasticity should be much higher than in the Finnish one (350 mm of bentonite with a Na-MM content of (75—90) % and a dry block density of about 1.7 g/cm^3 [39]). To some extent, this requirement is satisfied by the integral thickness of the bentonite blocks and the pellet layer (see Figure 2).

To reduce the CB density (to make the blocks sufficiently "loose"), one should consider the minimum swelling pressure criterion (see 2.1.1. Swelling pressure) and the mechanical strength of saturated bentonite, which is supposed to keep the containers in a given position.

In this regard, the use of 10X-based CB (Ca-MM relatively low in smectite) under this concept may turn out to be problematic due to its much lower ductility compared to Na-bentonites.

Conclusions

To evaluate an alternative concept proposed for RW-1 disposal at the Yeniseiskiy site, i.e., horizontal disposal layout with copper coated containers installed into CB blocks, a few design options differing in container and package wall thickness were considered. A forklift may be used under a design option providing for two VHLW drums emplacement into a single container. Further design optimization is possible, for example, CB thickness can be reduced given an increase in the container wall thickness, CB and DB size may be reduced assuming less rigid requirements to buffer heating. However, such an optimization would require an integrated approach and, in particular, due account of the long-term radiation safety of the DGR. Remote package handling methods would contribute to greater buffer and container thickness (its weight and size characteristics are not limited by the forklift's lifting parameters) with three VHLW drums emplaced into a single container nevertheless rendering the package handling process much more difficult and increasing the final disposal costs.

Relatively thin-walled container along with a thin copper coating would contribute to more ridged requirements for RW-1 package integrity. This study explores buffer parameters, namely, its swelling pressure, susceptibility to erosion, resistance to shear loads that were reduced to the content and type of montmorillonite and the dry density of bentonite. Despite the preliminary and evaluative nature of this study, we believe that several fairly important conclusions can be drawn on its basis.

For example, the use of 10X bentonite based on Ca-MM as a buffer under the considered disposal concept should provide for a quite high minimum required CB dry density (> 1.7 g/cm^3), which, from an engineering perspective, may turn to be barely attainable. On the other hand, a high-density buffer with a low plasticity may cause some problems associated with container resistance to shear rock loads driven by seismic impacts.

Exclusive use of Na-MM under the considered concept seems to be quite unlikely due to its tendency to mechanical erosion and transformation into Ca-MM driven by high intensity GW flows in EDZ evolving around the excavations.

Further optimization of the bentonite buffer and its composition would require some additional research to explore the factors that have not been considered in the present study (temperature and chemical resistance, possible negative impacts on adjacent safety barriers, flow characteristics relevant for the long-term DGR safety, etc.). Current findings suggest that bentonite with a predominant Na-MM content and a minimum required dry density (about 1.6 g/cm^3) would better suit as the main buffer material (CB blocks surrounding the container) with the gaps between the excavation walls and the blocks filled with Ca-MM bentonite pellets characterized with the maximum achievable dry density. It is believed that this design option may provide sufficiently high density and plasticity of the buffer and its adequately long-term chemical resistance.

References

1. Dorofeev A. N., Bolshov L. A., Linge I. I., Utkin S. S., Saveleva E. A. 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.

2. *Kryukov O. V.* Strategiya sozdaniya punkta glubinnogo zakhoroneniya RAO [Strategy for the development of RW deep disposal facility]. *Radioaktivnye otkhody — Radioactive Waste,* 2018, no. 2 (3), pp. 114—120.

3. Materialy obosnovaniya litsenzii na razmeshchenie i sooruzhenie ne otnosyashchegosya k yadernym ustanovkam punkta khraneniya RAO, sozdavaemogo v sootvetstvii s proektnoi dokumentatsiei na stroitel'stvo ob"ektov okonchatel'noi izolyatsii RAO (Krasnoyarskii krai, Nizhne-Kanskii massiv) v sostave podzemnoi issledovatel'skoi laboratorii (vklyuchaya materialy otsenki vozdeistviya na okruzhayushchuyu sredu) [Materials supporting siting and construction license application for a radioactive waste disposal facility not being considered as a nuclear facility established in accordance with the design documentation for the construction of facilities intended for the final disposal of radioactive waste (Krasnoyarsk Territory, Nizhnekanskiy rock mass) as part of an underground research facility (including environmental impact assessment materials)]. Volumes I—IV. Moscow, FSUE NO RAO Publ., 2015. — URL: *http://www.norao.ru/ecology/mol/* (accessed on: 01.10.2018).

4. Bogatov S. A. Zakhoronenie osteklovannykh VAO v vertikal'nykh skvazhinakh s tsementnoi zakladkoi – plyusy i minusy s tochki zreniya obespecheniya dolgovremennoi bezopasnosti PGZRO [HLW Disposal of in Verticale Deposition Holes with Cement Backfill — Pro and Contra with Regard to Long Term Safety of Geological Disposal Facility]. *Radioaktivnye otkhody — Radioactive Waste,* 2018, no. 1 (2), pp. 21—33.

5. Bogatov S. A., Kryuchkov D. V., Pavlov D. I., Sychenko D. V. Analiz razlichnykh kontseptsii zakhoroneniya RAO klassa 1 v kristallicheskikh porodakh [Analysis of Various Concepts for RW Class 1 Disposal in Crystalline Rocks]. *Radioaktivnye otkhody — Radioactive Waste,* 2020, no. 3 (12), pp. 66—77. DOI: 10.25283/2587-9707-2020-3-66-77.

6. Beygul V. P. Kontseptsiya gorizontal'nogo zakhoroneniya radioaktivnykh otkhodov 1 klassa v PGZRO [The concept of horizontal radioactive waste Class 1 disposal in DGR]. URL: *https://www.atomic-energy.ru/articles/2022/03/23/123033* (accessed on: 12.08.2022).

7. Martynov K. V., Zakharova E. V., Kulyukhin S. A. Alternative Conceptual Designs of Safety Barriers Proposed for Deep RW Class 1 Disposal at the Yeniseiskiy Site in the Nizhnekanskiy Rock Mass. *Radioaktivnye otkhody — Radioactive Waste,* 2022, no. 2 (19), pp. 68—84. DOI: 10.25283/2587-9707-2022-2-68-84.

8. Noronha J. Deep Geological Repository Conceptual Design Report. Crystalline / Sedimentary Rock Environment. Nuclear Waste Management Organization, APM-REP-00440-0015 R001, May 2016. 191 p. URL: *https://www.nwmo.ca/~/media/Site/Reports/2016/06/08/10/03/APM_REP_00440_0015_R001.ashx?la=en* (accessed on: 12.08.2022).

9. Bogatov S. A., Blokhin P. A., Kozlov P. V., Lukin S. A., Kiselev A. I., Remizov M. B., Semenov M. A., Utkin S. S. Osteklovannyye vysokoaktivnyye otkhody FGUP "PO "Mayak" — usrednennyye otsenki udel'noy aktivnosti i teplovydeleniya i ikh neopredelennosti [Vitrified high-level waste from FSUE PA Mayak — average estimated specific activity and heat release and relevant uncertainties]. *Voprosy radiatsionnoy bezopasnosti — Radiation Safety Issues,* 2021, no. 3 (103), pp. 3—12.

10. Keech P. G., Vo P., Ramamurthy S., Chen J., Jacklin R., Shoesmith D. W. Design and development of copper coatings for long term storage of used nuclear fuel. *Corrosion Engineering, Science and Technology,* 2014, vol. 49, no. 6, pp. 425—430.

11. Dzhurinskiy D., Dautov S., Shornikov P., Akhatov I. S. Strain gradient plasticity modeling to evaluate material plastic deformation behavior in Cold Gas Dynamic Spray Process. Conference: ITSC 2021. DOI: 10.31399/asm.cp.itsc2021p0256. URL: *https://www.researchgate.net/publication/352484950_Strain_Gradient_Plasticity_Modeling_to_Evaluate_Material_Plastic_Deformation_Behavior_During_Cold_Gas_Dynamic_Spray_Process* (accessed on: 09.08 2022).

12. Remizov M. B., Kozlov P. V., Logunov M. V., Koltyshev V. K., Korchenkin K. K. Kontseptual'nyye i tekhnicheskiye resheniya po sozdaniyu na "PO "Mayak" ustanovok osteklovyvaniya tekushchikh i nakoplennykh zhidkikh VAO [Conceptual and technical solutions for the development of installations designed for the vitrification of current and accumulated liquid HLW inventory at PA Mayak]. *Voprosy radiatsionnoy bezopasnosti — Radiation Safety Issues,* 2014, no. 3, pp. 17—25.

13. NP-093-14. *Federal'nyye normy i pravila v oblasti ispol'zovaniya atomnoy energii. Kriterii priyemlemosti radioaktivnykh otkhodov dlya zakhoroneniya* [Federal Norms and Rules in the Field of Atomic Energy Use. Acceptance Criteria for Radioactive Waste Disposal]. Moscow, Federal Service for Ecological, Technological and Nuclear Supervision Publ., 2014. 25 p.

14. Bogatov S. A., Kryuchkov D. V. *Otsenka minimal'noy tolshchiny obolochki stal'nogo konteynera dlya zakhoroneniya RAO klassa 1 v kristallicheskikh porodakh s bentonitovym buferom* [Estimated minimum thickness of a steel container shell for Class 1 radioactive waste disposal in crystalline rocks with a bentonite

buffer]. Preprint IBRAE № IBRAE-2020-04. Moscow, Nuclear Safety Institute of RAS Publ., 2020. 29 p.
15. Hall D. S., Behazin M., Binns W. J., Keech P. G. An evaluation of corrosion processes affecting copper-coated nuclear waste containers in a deep geological repository. *Progress in Materials Science,* 2021, vol. 118. URL: *https://www.sciencedirect.com/science/article/pii/S0079642520301304.* (accessed on 21.08.2022).
16. *Reshenie sektsii No. 1 "Ehkologicheskaya i radiatsionnaya bezopasnost' punktov dolgovremennogo khraneniya, konservatsii i zakhoroneniya RAO" NTS No. 10 Goskorporatsii "Rosatom" "Ehkologiya i radiatsionnaya bezopasnost'" po voprosu "Podgotovka iskhodnykh tekhnicheskikh trebovanii i programmy rabot po sozdaniyu lineiki upakovok RAO 1 klassa"* [Decision of section No. 1 Environmental and Radiation Safety of Long-term Storage, Isolation and Disposal of Radioactive Waste STC No. 10 of the State Corporation Rosatom Ecology and Radiation Safety on the Development of Initial Engineering Requirements and Work Program for the Serial Production of RW Class 1 Packages]. May 13, 2022.
17. Dizel'nyi pogruzchik TCM FD230-2 [Diesel loader TCM FD230-2]. URL: *https://centr-teh.ru/category-vilochnye-pogruzchiki-avtopogruzchiki-dizelnye/gruzopodemnost/23-tonni* (accessed on: 12.08.2022).
18. OSPORB-99/2010. *Osnovnye sanitarnye pravila obespecheniya radiatsionnoi bezopasnosti* [Basic Sanitary Rules for Radiation Safety (OSPORB-99/2010)].
19. Juvankoski M. *Buffer Design.* 2012. Posiva Working Report 2012–14. August 2013. 259 p.
20. Meleshyn A. Y., Zakusin S. V, Krupskaya V. V. Swelling Pressure and Permeability of Compacted Bentonite from 10th Khutor Deposit (Russia). *Minerals,* 2021, vol. 11, no. 7, pp. 742. URL: *https://www.mdpi.com/2075-163X/11/7/742* (accessed on: 07.12.2022).
21. Karnland O., Olsson S., Nilsson U. *Mineralogy and sealing properties of various bentonites and smectite-rich clay materials.* SKB TR-06-30. December 2006. 112 p.
22. Krupskaya V. V., Zakusin S. V., Lekhov V. A., Dorzhieva O. V., Belousov P. E., Tyupina E. A. Izolyatsionnye svoistva bentonitovykh bar'ernykh sistem dlya zakhoroneniya radioaktivnykh otkhodov v Nizhnekanskom massive [Buffer Properties of Bentonite Barrier Systems for Radioactive Waste Isolation in Geological Repository in the Nizhnekanskiy Massif]. *Radioaktivnye otkhody — Radioactive Waste,* 2020, no. 1 (10), pp. 35—55. DOI: 10.25283/2587-9707-2020-1-35-55.
23. Kurosawa S., Yui M., Yoshikawa H. Experimental Study of Colloid Filtration by Compacted Bentonite. *MRS Proc.,* 1996, vol. 465, pp. 963—970.
24. Stroes-Gascoyne S., Hamon C. J., Dixon D. A., Kohle C. L., Maak P. The Effects of Dry Density and Porewater Salinity on the Physical and Microbiological Characteristics of Compacted 100% Bentonite. *MRS Online Proc. Libr.,* 2007, vol. 985, no. 1, p. 1302.
25. Pedersen K., Motamedi M., Karnland O., Sandén T. Cultivability of microorganisms introduced into a compacted bentonite clay buffer under high-level radioactive waste repository conditions. *Eng. Geol.,* 2000, vol. 58, no. 2, pp. 149—161. DOI: 10.1016/S0013-7952(00)00056-9.
26. Martynov K. V., Zharkova V. O., Zakharova E. V. Deformatsiya i fil'tratsiya v glinistykh materialakh dlya zashchitnykh bar'erov radiatsionno opasnykh ob"ektov [Deformation and Filtration in Clay Materials Constituting to the Safety Barriers of Radiation Hazardous Facilities]. *Radioaktivnye otkhody — Radioactive Waste,* 2021, no. 4 (17), pp. 78—88. DOI: 10.25283/2587-9707-2021-4-78-88.
27. Johnsson A., Sandén T. System design of backfill Pellet optimization. R-13-47. Stockholm, 2013. 25 p.
28. Kim C.-S., Man A., Dixon D., Holt E., Fritzell A. *Clay-Based Pellets for Use in Tunnel Backfill and as Gap Fill in a Deep Geological Repository: Characterisation of Thermal-Mechanical Properties.* NWMO Report TR-2012-05. December 2012. 121 p.
29. Fried J. J., Combarnous M. A. Dispersion in Porous Media. In: *Advances in Hydroscience.* Edited by V. T. Show. 1971. Vol. 7. Pp. 170—282.
30. Börgesson L., Karnland O., Johannesson L. E., Gunnarsson D. *Current Status of SKB's Research, Development and Demonstration Programme on Buffer, Backfill and Seals.* A Report Prepared by SKB for United Kingdom Nirex Ltd. SKB IC. 122. 2006.
31. Pintado X., Adesola F., Turtiainen M. *Downscaled Buffer Tests.* Posiva Working Report 2012-100. Eurajoki, Finland, Posiva Oy, 2013.
32. Sandén T., Börgesson L. Early effects of water inflow into a deposition hole. Report R-10-70. Laboratory tests results. Stockholm, Sweden, SKB. 2010. 74 p.
33. Sane P., Laurila T., Olin M., Koskinen K. *Current status of mechanical erosion studies of bentonite buffer.* Posiva 2012-45. Eurajoki, Finland, Posiva Oy, 2013.
34. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto.* Performance Assessment 2012, Posiva 2012-04. February, 2012. 528 p.
35. Neretnieks I. *Flow and transport through a damaged buffer — exploration of the impact of a cemented and an eroded buffer.* SKB TR-06-33. December 2006. 36 p.
36. Raiko H., Sandström R., Rydén H., Johansson M. *Design analysis report for the canister.* SKB TR-10-28. Svensk Kärnbränslehantering AB, 2010. 80 p.
37. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto — Models and Data for the Repository System 2012.* Posiva 2013-01, Part 1, 2. September 2013.
38. Raiko H. (ed.), Pastina B., Jalonen T., Nolvi L., Pitkänen J., Salonen T. *Canister Production Line 2012.*

Design, Production and Initial State of the Canister. Posiva 2012-16. December 2012. 182 p.
39. Juvankoski M., Ikonen K., Jalonen T. *Buffer Production Line Design, Production and Initial State of the Buffer.* Posiva 2012-17. 2012. 166 p.
40. Börgesson L., Pusch R. *Rheological properties of a calcium smectite.* SKB Technical Report 87-31. December 1987. 130 p.
41. Dueck A., Börgesson L., Johannesson L. E. *Stress-strain relation of bentonite at undrained shear. Laboratory tests to investigate the influence of material composition and test technique.* SKB Technical Report TR-10-32. December 2010. 54 p.
42. *Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories.* Edt. by C. Davies, F. Bernier. Publications Office, 2005.
43. Bäckblom G. *Excavation damage and disturbance in crystalline rock — results from experiments and analyses.* SKB Technical Report TR-08-08. November 2008. 77 p.
44. *Data report for the safety assessment SR-Site.* Svensk Kärnbränslehantering AB, Technical Report TR-10-52, December 2010. 458 p.
45. Zhao C., Hobbs B., Ord A., Hornby P., Peng S., Liu L. Theoretical and Numerical Analyses of Pore-fluid Flow Patterns Around and Within Large Cracks and Faults. *Geophys. J. Int.,* 2006, vol. 166, pp. 970—988.
46. Bogatov S. A., Kryuchkov D. V. *Uproshchennaya model' perenosa radionuklidov v treshchinovatykh kristallicheskikh porodakh dlya predvaritel'nykh otsenok bezopasnosti zakhoroneniya RAO klassa 1 na uchastke Yeniseyskiy* [Simplified model of radionuclide transport in fractured crystalline rocks considered under the preliminary safety assessments of RW Class 1 Disposal at the Yeniseiskiy site]. Proceedings of the 10th Russian Scientific Conference Radiation Protection and Radiation Safety in Nuclear Technologies. Moscow, October 26—29, 2021. Vol. 3. Moscow, NSI RAS Publ., 2022. Pp. 314—322.
47. Birgersson M., Börgesson L., Hedström M., Karnland O., Nilsson U. *Bentonite erosion.* Final report. SKB Technical Report TR-09-34. December 2009. 164 p.
48. Ozerskiy A. Yu., Karaulov V. A. Gidrogeologicheskiye issledovaniya pri izyskaniyakh massiva kristallicheskikh porod dlya podzemnogo stroitel'stva v yuzhnoy chasti Yeniseyskogo kryazha [Hydrogeological studies during the exploration of a crystalline rock mass proposed for underground construction in the southern part of the Yeniseiskiy Ridge]. *Inzhenernyye izyskaniya — Engineering survey,* 2012, no. 11, pp. 52—59.
49. Pont A., Coene E., Idiart A. *Bentonite erosion project. Preliminary study for the numerical simulation of bentonite erosion.* SKB Report P-20-16. August 2020. 55 p.
50. Moreno L., Neretnieks I., Liu L. *Modelling of erosion of bentonite gel by gel/sol flow.* SKB Technical Report TR-10-64. November 2010. 48 p.

Information about the authors

Bogatov Sergey Aleksandrovich, PhD, Senior Researcher, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: sbg@ibrae.ac.ru.

Drobyshevsky Nikolay Ivanovich, PhD, Senior Researcher, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: dni@ibrae.ac.ru.

Krupskaya Victoria Valerievna, Ph.D. in Geological and Mineralogical Sciences, Senior Researcher, Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of the Russian Academy of Sciences (35, Staromonetny per., Moscow, 119017, Russia); Senior Researcher, Lomonosov Moscow State University (1, Leninskie Gory, Moscow, 119991, Russia), e-mail: krupskaya@ruclay.com.

Zakusin Sergey Vyacheslavovich, Junior researcher, Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of the Russian Academy of Sciences (35, Staromonetnyy per., Moscow, 119017, Russia); Lomonosov Moscow State University (1, Leninskie Gory, Moscow, 119991, Russia), e-mail: zakusinsergey@gmail.com.

Lekhov Vladimir Alekseyevich, PhD, Senior researcher, Lomonosov Moscow State University (1, Leninskie Gory, Moscow, 119991, Russia), e-mail: v.lekhov@gmail.com.

Bibliographic description

Bogatov S. A., Drobyishevskiy N. I., Krupskaya V. V., Zakusin S. V., Lekhov V. A. Preliminary Assessment of Engineered Barrier Parameters under DGR Concept with Horizontal Orientation of RW Packages in Copper Coated Containers. *Radioactive Waste,* 2023, no. 3 (24), pp. 77—91. DOI: 10.25283/2587-9707-2023-3-77-91. (In Russian).