ANALYSIS OF VARIOUS CONCEPTS FOR RW CLASS 1 DISPOSAL IN CRYSTALLINE ROCKS

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The paper considers most elaborated and mature concepts for SNF and HLW disposal in crystalline rocks. It explores in detail an alternative concept suggesting the use of a super-container (SC) with a bentonite buffer located inside a steel body and the SC itself located in vertical wells inside a cement backfill, which is also used to seal fractures crossing the wells.

Keywords: *geological disposal, crystalline rocks, super-container, bentonite buffer, cement backfill, radioactive waste.*

Intensive efforts focused on the development of SNF/HLW disposal concepts in crystalline rocks were launched over 30 years ago [1] with great uncertainties in the predictions dealing with the evolution of engineered barrier materials and bed rocks. To a large extent, the lack of knowledge was made up by a large “margin” of safety in the applied design and technical solutions. To date, KBS-3 type RWDF concepts (see below) gained most widespread acceptance worldwide with extensive knowledge on the safety issues accumulated turning them to some extent into a standard of geological disposal in crystalline rocks.

However, these concepts require the compliance with rather stringent rock acceptability criteria during design development, work planning, research and RWDF construction with some extremely costly and complex engineering solutions to be implemented as well. Thus, a question arises whether it is possible to optimize these concepts taking into account the accumulated experience and data on the applied protective barriers under geological disposal conditions.

This article focuses one possible solution providing such optimization considering its potential further application also for planning purposes and relevant experiments to be conducted in the underground research laboratory (hereinafter referred to as URL) in the Nizhnekansk rock mass. Several reasons for this can be noted. Firstly, analytical methods, calculation tools, technologies are constantly evolving. Therefore, safety important solutions assumed as feasible some decades ago can be greatly refined and elaborated now. These are the general principles of scientific and technological progress in all industrial areas. Secondly, recently reactor and radiochemical technologies have been actively developed in Russia obviously entailing new opportunities regarding both RW conditioning technologies and the container fleet. In this regard, certain variability in the layouts of the underground RWDF sections is seen as a necessary and reasonable option. Thirdly, Russian URL should contribute to the global knowledge on geological disposal with its operation providing for the engagement of national RW disposal operators and scientific and technical support organizations from all over the world.

Obviously, comprehensive safety demonstration for a new concept dealing with such a complex facility as RWDF will require extensive efforts with multiple factors contributing to the success attained in this field. However, considering available global experience we believe that at least preliminary safety assessments of the new concept can be done in a rather prompt manner. Early assessments should demonstrate whether its further more in-depth elaboration and refinement can be considered feasible.

Available RWDF layouts in crystalline rocks

An overview of globally recognized VHLW and SNF disposal concepts is provided in [4]. Options addressing crystalline bedrocks consider either vertical or horizontal RW package emplacement with an external buffer made of compacted bentonite (Figure 1) or the use of multi-purpose containers (MPC). MPC are used for storage, transportation and disposal purposes in RW deep disposal facilities (RW DDF) for SNF or HLW.

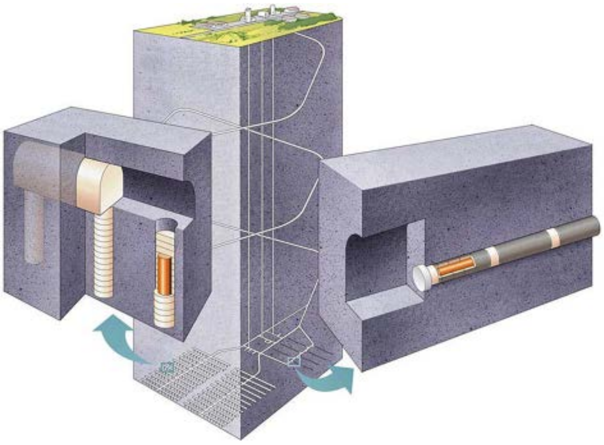

Figure 1. Layout of a disposal system suggesting vertical or horizontal orientation of SNF/VHLW containers with compacted bentonite buffer [5]

KBS-3 concept developed by Swedish company Svensk Kärnbränslehantering AB (SKB) and currently being actively implemented in Sweden and Finland is considered as the most globally accepted concept proposed for SNF disposal in crystalline rocks at a depth of about 500 m. KBS-3V is considered as the most mature concept suggesting vertical orientation of disposal packages (Figure 2) with SNF assemblies loaded into sealed copper containers with a cast iron insert. The containers are installed one at a time into vertical boreholes with pressed (compacted) bentonite used as a buffer

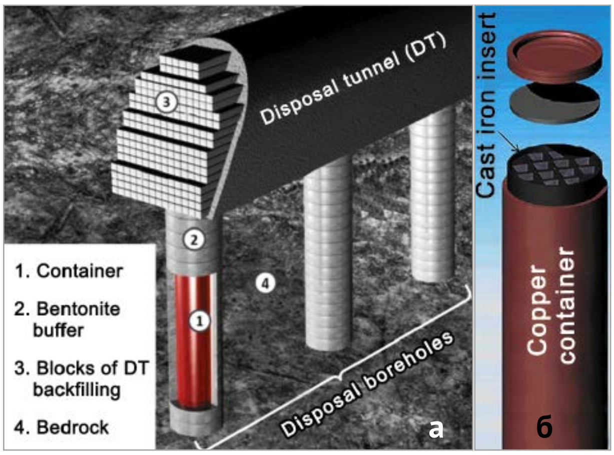

Figure 2. KBS-3V concepts (a) and copper SNF container design (b) [6]

material. Disposition tunnels above the disposal boreholes are backfilled with bentonite or its mixture with other materials. Under this concept, the packaging is believed to be provide containment for hundreds of thousands of years.

Another concept suggesting horizontal emplacement of SNF/VHLW packages (KBS-3H) has been developed by SKB and Finnish company Posiva since late 1990's simultaneously with the KBS-3V concept. KBS-3H engineered barrier system is similar to KBS-3V nevertheless implying the use of so-called super-containers (SC). SC are structures assembled on the surface with primary RW packaging, loadbearing cast-iron insert, copper container and a buffer made of compacted bentonite rings installed into a perforated metal shell. The diameter of horizontal excavations exceeds SC diameter by only 5 cm, and this gap is filled with swelling bentonite through the perforated shell. This concept enables more efficient use of the underground space (in contrast to KBS-3V, there are no empty horizontal excavations that require backfilling), reduces shears in vertical wells. Since the structure is assembled on the surface, a more dense buffer can be more effectively accommodated around the outer container.

Another favorable aspect of SC application is the uneven swelling and cracking of bentonite blocks in the FEBEX experiment [7, 8] (Full-scale Engineered Barrier Experiment with a heater installed into a horizontal borehole simulating a canister with heat-generating RW surrounded by cylinder-shaped blocks made of compacted bentonite). The experiment was performed in heavily saturated crystalline rocks: cracking involving block displacement occurred due to premature bentonite swelling.

Implementation of KBS-3H is challenging not only due to the drilling of horizontal boreholes with a diameter of about 2 m and a length of about

300 m, but also the use of a rather complex device designed to move the package in the wells using a pallet on a hydraulic cushion (Figure 3). Since SC and the sealing blocks are moved at a relatively slow pace, jamming of structures inside the excavations due to unfavorable premature swelling of bentonite can occur.

Safety of KBS-3 concept considering its both modifications was quite thoroughly demonstrated back in 2011—2012 [7—10].

Distinctive features of the KBS-3 concept can be summarized as follows.

1. Crystalline rocks at a disposal depth of less than 400—600 m are not considered as the main safety barrier. The main barrier function is performed by disposal container, the design of which in combination with other barrier materials shall maintain its integrity for at least hundreds of thousands of years[1].

2. High standards for the buffer quality (bentonite and its dry density) and the accuracy of its installation: minimum gaps between the container and the buffer, as well as those between the buffer and the rock. Due to large gaps the saturated density of bentonite can decrease to a level below the minimum acceptable one.

3. KBS-3 concept is sensitive to potential uneven swelling of bentonite and its washout (erosion). Hence, some stringent requirements are imposed on the quality of bed rock (absence of large water-conducting fractures crossing the wells). Under KBS-3V concept, flexibility of RWDF layout allows to address this challenge: one can always find a suitable bedrock section for a short well designed only for one waste package (albeit by increasing the space area of underground disposal sections). KBS-3H uses high-density bentonite, well plugging and artificial uniform irrigation of the filled sections to prevent uneven swelling of bentonite in the SC and insulating sections.

4. Attempts to install more than one container into one vertical borehole will prompt some difficulties in providing the required gaps and (if preventive well plugging is not in place) the inability to use large amounts of bedrocks: the deeper the well, the more likely it will be crossed by water-conducting cracks. Under KBS-3H concept, rather complex and cumbersome paving machine with a pallet moving on a hydraulic cushion will have to be transported to the underground sections or assembled in underground excavations, which seems quite problematic considering the size of the mine cage (5 × 2 m).

The Japanese H12 concept is somewhat different from KBS-3: packages with VHLW from PWR-type reactor SNF reprocessing will be installed into carbon steel containers emplaced into vertical wells or horizontal tunnels. Sand-bentonite mixture (bentonite/sand weight ratio accounting for 70 : 30) is proposed as a buffer material [11]. H12 concept developed for crystalline rocks suggests the disposal depth of about 1,000 m.

The latter concept suggests that MPC containing about 20 canisters with VHLW or fuel assemblies

[1] Under the Japanese H12 concept, disposal depth accounts for some 1,000 m with the rock being considered as a self-sufficient safety barrier

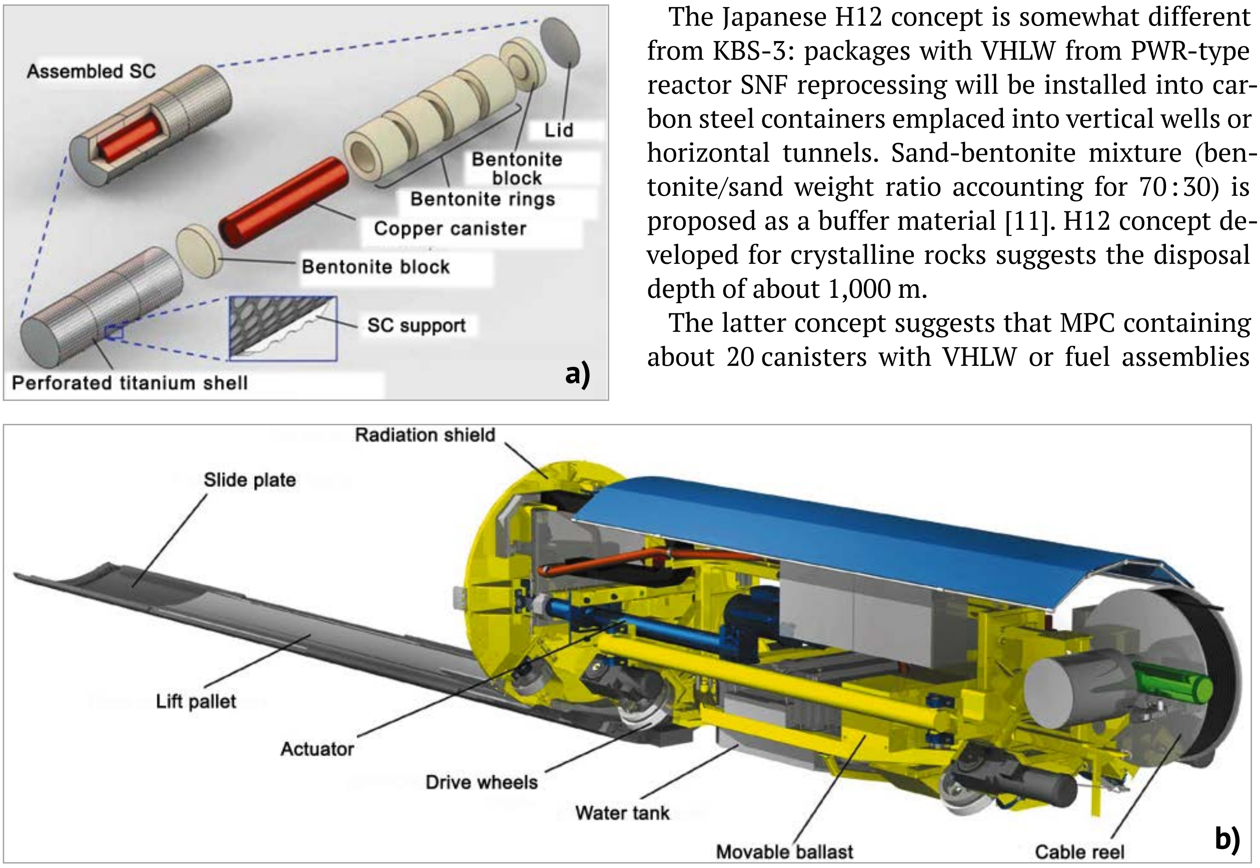

Figure 3. Supercontainer designs [5] (a) and disposition machine for SC installation into a horizontal borehole (b) [9]

with SNF each are emplaced vertically into large ventilated excavations and held there for some 300 years, during which the packages are cooled and monitored. Upon attaining adequate temperature level, , excavations with MPCs are backfilled with cement or compacted bentonite [12, 13]. Until recently, this concept was considered mainly due to two circumstances: (a) concerns raised over the challenges associated with waste retrieval (if such a decision is made after a long-term interim storage period) in case of other layout options, and (b) in some cases, according to national legislation, the RW disposal operator shall buy out a plot of land intended for RWDF construction. The latter case suggests that after a long cooling time, denser VHLW emplacement layout is possible, thus, decreasing the space area required for its disposal. To date, this option is considered mainly as a promising one when it comes to the management of future HLW streams since their heat release, especially when it comes to addressing the challenge of NFC closure, can be one order greater than the one of accumulated HLW. This concept is the least mature in terms of long-term safety.

Considering such RWDF layout, it seems quite challenging to install a compacted bentonite buffer with a required dry density around the MPC. Whereas, due to large uncertainties in the long-term evolution of cement materials under deep disposal conditions, the use of cement buffer for VHLW disposal in crystalline rocks is currently considered as an insufficiently mature method. Moreover, typical size of the excavations under this concept accounts for 10–20 m in width and height, which is several times larger compared to other concepts. Production and transportation of large-sized MPCs is quite expensive.

Proposed SC concept and its evaluation

For the first time, the idea of EBS system designs with a buffer located in the outer carbon steel shell envisaged as a container manufactured on the surface was proposed in [14]. A combined package containing VHLW, a buffer and a protective shell could be transported and immediately disposed of in DDF RW. Under this concept [14], primary VHLW were placed directly into the buffer enclosed into a thick steel shell (Figure 4). In contrast to SC concept shown in Figure 3a, the buffer and the protective container are swapped.

Preliminary estimated container thickness was specified at least to ensure adequate strength under hydrostatic pressure of 5 MPa, the weight of the above containers, as well as to maintain the integrity of VHLW container given the corrosion processes

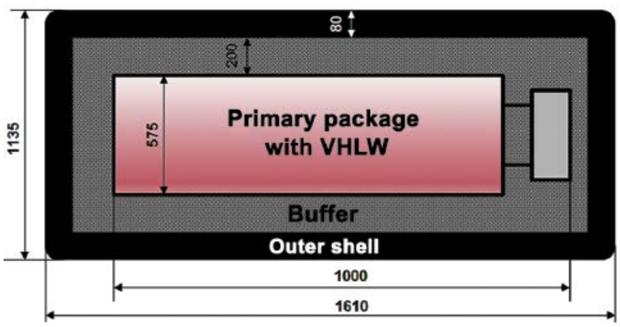

Figure 4. SC concept [16] with SC dimensions estimated for screening calculations

evolving over a period of at least 50,000 years. Detailed calculations, due to their large extent, will be provided in a later study.

Figure 5 presents a general layout of the SC assembly proposed under the new concept. First, bottom (base) and side parts of the bentonite buffer (rings) made of compacted bentonite are assembled in an open outer container. Then, the canister(s) with VHLW is (are) lowered into the cavity formed by the bentonite rings. The gap between the canister and the buffer (~ 1—2 cm) is backfilled with powdered bentonite with additives capable of reducing the leaching of aluminophosphate glass (glass powder of the same composition) or acting as a neutron absorber (ensuring subcriticality of the SC stack in the well). Then the backfill is compacted to increase the dry density, buffer assembly operations are completed by the installation of a top cover made of compacted bentonite. A weld-on lid is installed on the outer container.

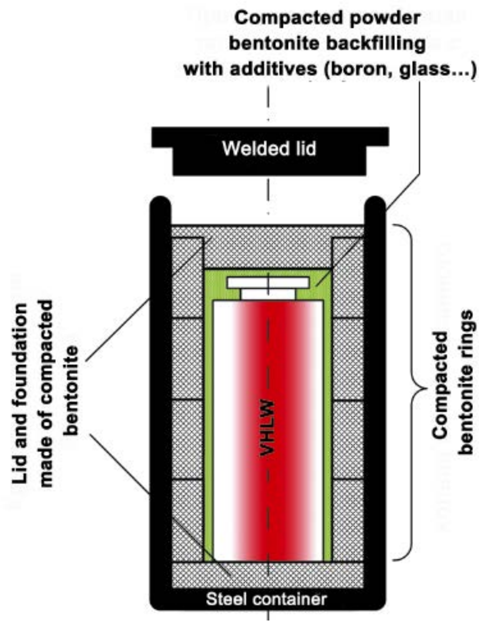

Figure 5. Layout of engineered barriers within an SC

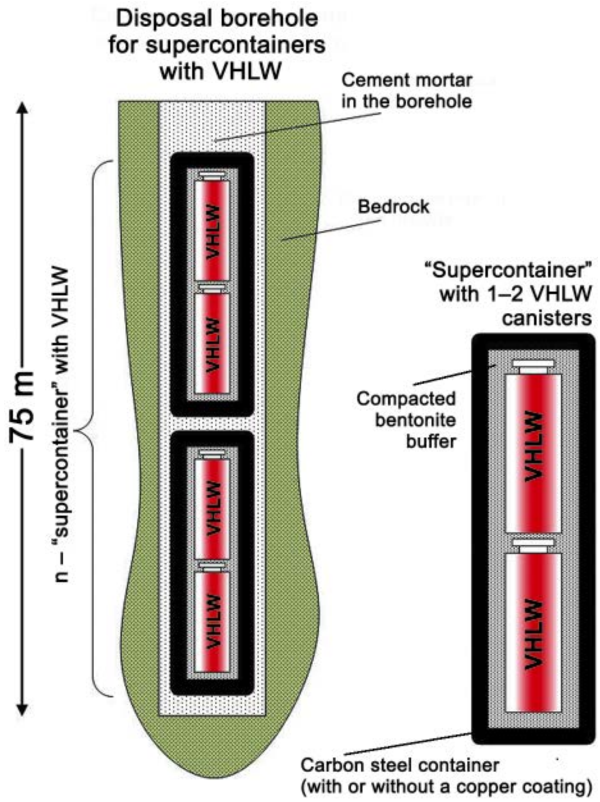

Figure 6. VHLW disposal options suggesting the use of newly developed SC designs

Newly developed SC designs suggest VHLW disposal in vertical boreholes being several tens of meters long (Figure 6). SC size containing one or two canisters with VHLW depends on the carrying capacity of the available equipment. During SC emplacement, boreholes are grouted (proposed method is for instance discussed in [15]). The number of boreholes and the distance between them depends on the required RW DDF capacity and restrictions on heat generation governing adequate strength capacity of SC and the cement backfill.

The above SC designs allow to address a number of challenges, namely:

- to reduce the pressure on the outer container due to lower gas evolution during anaerobic corrosion (since the rate of steel corrosion decreases significantly in the cement backfill), no pressure impact from swelling bentonite and corrosion products on the outer shell of the container. Under these circumstances minimum thickness of the outer metal container can be reduced;
- allow significantly higher SC heating since bentonite remains practically dry for a long time (until the integrity of the outer container is breached) and does not degrade: all known mechanisms of bentonite degradation can be only triggered if a liquid phase is available;
- to impose less stringent requirements on SC acceptability criteria considering the cracks crossing the disposal wells, since erosion ("washing out") of bentonite by groundwater is deemed impossible and, in contrast to the external bentonite buffer, cement can be used to seal the cracks crossing the boreholes.

Long-term safety concept assumed under the proposed VHLW disposal option is based on relevant properties of a multi-barrier system. Protective barriers (according to the pattern governing potential spread of radionuclides leaching out from VHLW) include: a bentonite buffer inside the SC, outer protective SC container, cement backfill inside the disposal borehole and the bedrocks.

Under conservative assumptions, glass VHLW matrix and the primary packaging (thin steel canister) are not considered as barriers. Most probably, the glass matrix, in addition to initial rather low protective properties of aluminophosphate glass, will get deformed under the asymmetric pressure of swelling bentonite after the integrity of the outer SC[1] shell is breached assuming that the VHLW canister is thin (4 mm) and is not leak-tight.

Cement backfilling will act as the first barrier preventing SC corrosion and degradation. Cement cracking is viewed as an inevitable process associated with its physical and chemical properties. At the early stage of cement hardening (about 2 days), cracking will be associated with its shrinkage, separation of the aqueous phase onto the surface, expansion due to exothermic reactions during hardening followed by compression during its cooling. However, given layer-by-layer application in a closed space, cement backfill hardening conditions, the low rate of moisture evaporation from the surface in the boreholes and backfill heating due to the heat release from VHLW in the SC will significantly reduce the number and the size of formed cracks as compared to the conditions considered common for concrete hardening [16].

According to conservative estimates, characteristic crack opening at the cement hardening stage will account for only some fractions of a millimeter. Further increase in the size and number of cracks in the cement backfill is not expected until the waste cools down and the SC body shrinks, as well as until a significant amount of steel SC corrosion products is formed (after several hundred years).

Depending on borehole location and properties of the surrounding bedrock, complete DDF RW saturation with ground water is expected not earlier than in a few decades [17]. Basically, under highly alkaline environment promoted by cement backfill,

[1] In case of positive long-term safety assessment findings requirements for VHLW glass matrix assumed under this concept can be sufficiently lowered as compared to those specified in NP-093-14

outer carbon steel container will corrode uniformly at a very low rate (~ 0.1 μm/year) [18].

Cement backfill degradation (its structure degradation and decrease in the pore water pH level) and corrosion of the outer SC shell will inevitably result in SC failure with the groundwater flowing into it. However, preliminary estimates demonstrate that given cement backfill thickness of some 30 cm this can occur no earlier than in 50—100 thousand years after DDF RW closure, when the heat release from the disposed waste becomes insignificant and the maximum temperature inside the SC is comparable to the temperature of the rock mass (about 5 °C)[1]. Subsequent more in-depth analysis should adequately consider the cement backfill degradation time that can be adjusted based on its thickness (borehole diameter), as well as the sealing of small fractures within the bedrock by calcite formed during cement degradation [19, 20].

The amount of some part of cement degradation products and especially of steel container corrosion products exceeds their initial volume. It's expected that after degradation, backfill volume will remain almost unchanged, the groundwater flow through the well may increase but only minorly compared to the one available at the time of complete DDF RW saturation.

The rate of groundwater inflow into the SC will depend on the hydraulic gradient; the water permeability of the surrounding bedrock and degraded cement backfill mixed with the corrosion products of the SC steel shell; the decompaction degree in the outer shell and the water permeability of bentonite inside the SC. The initial size of the decompaction area in the SC body will be small depending on potential defects (mainly in the weld seam) of the metal. Most probably these will be plugged with expanding (swelling) bentonite. Most probably due to uniform corrosion, decompaction area in the SC shell resulted from crack formation after a significant loss of its thickness will be also plugged by swelling bentonite. Substantial degradation of the outer shell due to uniform corrosion and, in fact, container failure, as well as radionuclide release into DDF RW bedrocks is supposed to occur much later.

Degradation of bentonite buffer inside the SC, which may be caused by inflowing alkaline groundwater, is not expected since SC failure can occur only after a significant decrease in the pH level of the pore water in the cement backfill.

If a SC with a copper outer surface coating is used, then its failure is supposed to occur much later compared to a steel SC[2] described above. However, it can be expected that, in any case, a significant SC failure will occur no earlier in 50,000 years, i. e. by the time when another climatic phase starts to evolve with an expected significant temperature fall up to bedrock freezing up to disposal depth. This period will last another 20,000-50,000 years: during this period radionuclide transfer with groundwater flow is not expected to occur.

Following a significant SC failure, the main barrier function is expected to be performed by swollen bentonite: together with the degraded cement backfill and steel SC corrosion products it will ensure the diffusion nature of radionuclide release from VHLW beyond the near-field of the disposal facility. Sorption characteristics of engineered barriers are expected to provide adequate sorption for the major part of radionuclides except for virtually non-absorbable long-lived anions.

Bedrock enclosing the DDF RW is considered as another protective barrier providing retardation of non-absorbable radionuclides for a characteristic time of several hundred years, as well as a decrease in the concentration of radionuclides and "blurring" the front edge of their plume spreading due to radionuclide matrix diffusion in the rocks.

Direct assessment of DDF RW radiation impacts on the biosphere, and particularly on the human population, are extremely challenging, since radionuclide release into the near-surface layer of the soil will occur after the ice age, namely, in some 200,000 years after DDF RW closure. For this timeframe, biosphere conditions and particularly the coefficients for radionuclide ingress into the surface layer of the soil and the expected exposure doses for population cannot be reliably predicted.

During the first 10,000 years when it is still possible to extrapolate existing behavioral characteristics of the population and climatic conditions, radiation impact on the population can be potentially produced only in case of an unexpected SC failure assumed under this concept as an emergency.

As already mentioned, the time during which the SC maintains its protective function can be significantly increased by means of applying a copper coating on its outer surface. As for the cement backfill, in addition to an obvious option suggesting

[1] The given quantitative estimates are considered as preliminary mainly based on DDF RW analogues and should be further quantitatively calculated using actual initial parameter values.

[2] In the KBS-3 concept, copper container thickness (approximately 5 cm) is basically specified based on engineering requirements. To ensure SC corrosion resistance, a 1cm-thick copper coating is sufficient. By present time, copper coating methods using electrolytic deposition or cold spraying have been mastered (see, for example, [21, 22]).

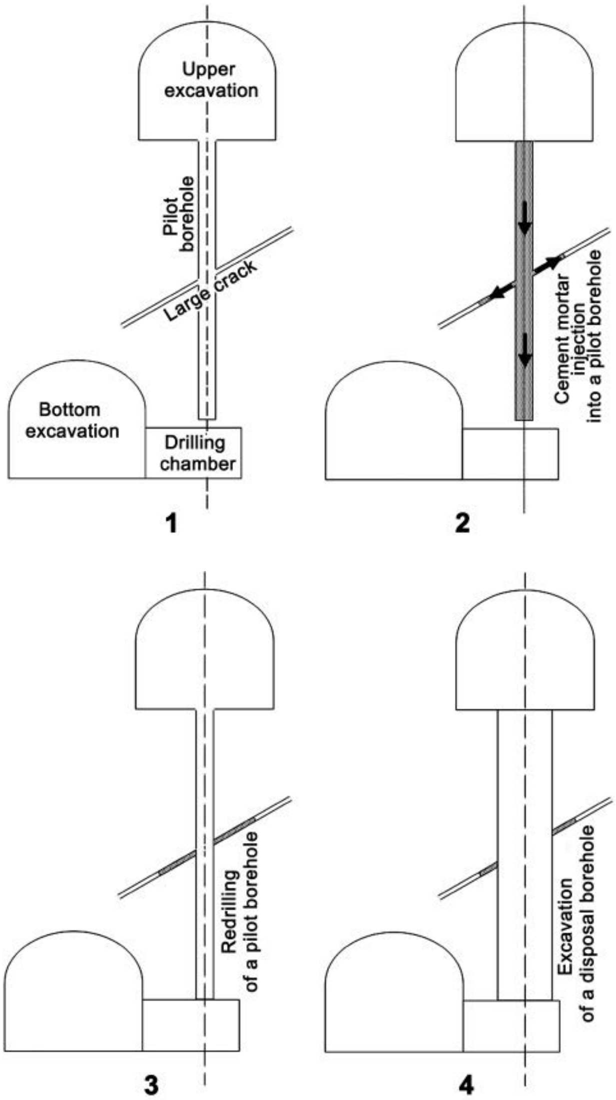

Figure 7. Method used to seal large cracks crossing the disposal boreholes (stages 1-4 explained, see the text)

the increase in its thickness[1], preliminary (before VHLW package disposal) sealing of large water-conducting cracks crossing the well may help to increase this time. Sealing should be performed by squeezing the grout into the fracture.

The sealing method requires further refinement; however, the following procedure has been tentatively proposed (Figure 7):

1. Pilot well drilling (without reaching the drilling chamber).

2. Cement mortar is pumped into the pilot well under high pressure. Mortar pressure should be sufficiently high for grout to flow into the large fractures crossing the pilot well, as well as the VHLW disposal well (after its drilling).

3. After grout solidification, the pilot well is drilled through the cement backfill again – this time up to its intercrossing with the drilling chamber. In this case, large cracks crossing the pilot well and the VHLW disposal well are sealed with cement mortar.

4. Disposal wells are drilled.

Less stringent requirements are expected in case of well isolation using a cement backfill compared to the bentonite one. However, if for some reason this method turns out to be inadequate for the crack sealing, "megapacker" type device can be applied [23, 24] with packers immediately intercepting a well section that requires sealing.

Potential simultaneous disposal of RW Class 2[2] considering cement as a buffer material is viewed as an additional advantage of the proposed concept along with greater mechanical strength of the SC and more favorable radiation-shielding characteristics. Under KBS-3 concepts with compacted bentonite proposed as a buffer, simultaneous disposal of RW with a cement buffer is considered unacceptable and such facilities should be spaced by at least 200—300 m [25]. Thick outer walls of the SC will provide its greater resistance in case of possible accidents, for example, if it falls into a mine shaft, and will facilitate further damaged SC management.

Concept implementation

In general, SC concept allows a matrix layout with the underground section involving two horizons and deep wells. Obviously, this solution can be considered as a middle ground, since not all of the issues associated with the depth of these wells can be handled, in particular:

- issues associated with packages falling to the bottom of the well;
- mechanization of operations at such depths appears to be quite challenging;
- providing adequate quality of backfilling operations in gaps between the container and the well;
- high probability of fracture zone intersection.

Special consideration should be given to the production of SC and its cost, in particular: copper spraying methods, production of compacted bentonite products, welding technologies and weld control for a thick-walled SC body and lid. Therefore, today it's hard to provide any estimates on SC costs.

[1] If the cement backfill is too thick, on the one hand, SC failure will occur at a later time, but on the other, after its degradation, bentonite may have a lower density after being swollen. Cement backfill thickness should be optimized using computational tools.

[2] Long-term radiation hazard presented by reactor graphite belonging to RW Class 2 is associated with practically non-absorbable ^{36}Cl, as well as ^{14}C for which the efficiency of cement buffer is not sufficient. Apparently, the best solution would be to use a bentonite buffer. If a decision is made on graphite disposal in the NKM DDF RW, the layout of the disposal system shall allow for "upstream" graphite emplacement and the minimization of negative impact potentially produced by cement leachates on the bentonite buffer.

Conclusion

Development of geological RW disposal facilities is associated with a number of specific features in terms of its arrangement as compared to other capital construction projects. These aspects are mainly due to: 1) geological uncertainties that can be handled only during actual project implementation (early in the project this can be done only by applying increasingly conservative safety assumptions); 2) contradiction between continuous (and sometimes basic, since the implementation timeframe for such projects amounts to several decades) advances in engineering and analytical method development, on the one hand, and available project documentation, on the other.

URL construction viewed as the first stage of DDF RW development, is aimed, in particular, at minimizing the influence of the abovementioned aspects.

The above study has demonstrated that among the considered "classical" concepts, KBS-3H can be viewed as essentially adequate. However, it entails some challenges associated with running in or subsurface assembling of a disposition machine required for waste package installation into horizontal wells. MPC concept, in addition to the high cost and insufficient maturity of a big number of its technical aspects, is, in fact, viewed as a deferred decision. The new approach considered in the article provides an acceptable level of safety under the "matrix" DDF RW concept.

Currently, several additional concepts viewed as potentially applicable in case of deep RW disposal in crystalline rocks, including horizontal orientation of waste packages and air cooling of radioactive waste in the underground section are being evaluated. In particular, studied is an option suggesting the installation of a thin-walled primary package into blind shallow vertical wells providing for thick bentonite buffer. To identify the optimal option that can be considered as a cost-effective one complying with all essential safety criteria, further study and comparison of most promising alternative concepts is required.

To further develop the SC concept and compare it with other alternative RW disposal options, additional R&D are required. According to present day knowledge, the most crucial R&Ds should be aimed at:

- specifying minimum SC thickness and the need of applying an anti-corrosion coating;
- decision making on the place where VHLW canisters should be loaded into SCs and development of an appropriate technology;
- study of cement material used to backfill SC in the wells, namely, of its long-term resistance and optimization of its parameters;
- development of and mastering the preventive sealing method for disposal wells.

Low maturity level and some issues considered essential in terms of predicting the long-term EBS evolution which were not previously considered in such a combination are viewed as the main disadvantage of the new concept. However, preliminary analysis performed gives causes for some optimism.

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