BOREHOLE RW DISPOSAL CONCEPT AND PROSPECTS OF ITS IMPLEMENTATION IN RUSSIA

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The paper evaluates the prospects of borehole disposal considering a number of solidified RW types generated at Russian enterprises, which was done based on analyzed world literature sources discussing the safety of radioactive waste storage facilities of mine and borehole types.

Keywords: *radioactive waste, geological disposal, borehole disposal concept.*

Introduction

Waste management organizations and scientific institutions in different countries periodically review and analyze the feasibility of various concepts focused on the geological disposal of radioactive waste (RW) and spent nuclear fuel (SNF). To date, at least three RW geological disposal concepts have been compared with each other in the world literature: mine-type repositories (MR), deep borehole disposal (DBD) and Disposal in Horizontal Drillholes (DHD) [1]—[3]. DBD is now and then presented as a more socially acceptable alternative to the MR option, the consensus on the prospects of which began to take shape as early as in the 1960s [4]. RW disposal in shallow boreholes is viewed as a separate topic, which is regulated by relevant regulations, for example, the IAEA Safety Guide [5]. A new edition of this Guide is being developed to take into account the experience gained and the recent developments in the borehole disposal concepts. It also mentions the DBD concept, in relation to which various remaining uncertainties are stated, for example, those associated with the rock heterogeneity or the ability to characterize them at such great depths [6].

MR designs are considered as most advanced in terms of their implementation, especially the Swedish KBS-3 designs providing for SNF disposal in crystalline rocks at depths of 400—1,000 m. A number of countries consider MR disposal options in clays, salts and other rocks [7]. The United States and the Great Britain are practically the only countries with a developed nuclear power industry that have been actively developing an alternative concept providing for RW disposal in boreholes drilled in crystalline basement rocks at a depth of up to 5,000 m [8], [9]. The DBD concept is being developed for long-lived RW disposal purposes in Australia [10] and is being considered in a number of other countries. In addition, the United States have been recently exploring the option providing for

RW disposal in long lateral sections of long drillholes excavated in clayey rocks of the sedimentary cover at depths of up to 600—1,500 m [11].

According to Federal Law No. 190-FZ, RW classification system involves six classes of waste depending on its activity, origin and state of aggregation. The concept of their disposal is tied to the RW classes. Near-surface disposal should be provided for RW Class 3 and 4. Deep mine-type repositories should be used to dispose of intermediate-level and high-level waste (ILW and HLW) of Class 1 and 2. The first section of a mine-type disposal facility intended for such R is planned to be constructed at the Yeniseiskiy site in the Krasnoyarsk Territory [12]. Conditionally borehole-type (injection into reservoir-beds) disposal practice have been implemented in the territory of the Russian Federation only to dispose of liquid RW at a depth of up to a kilometer and has been successfully performed on an industrial scale since the late 1960s [13], [14]. This article evaluates the potential of borehole-type disposal systems for those solid (solidified) RW the decision about the disposal method of which has not yet been made in the Russian Federation (liquid waste is not discussed in this article).

Success in the implementation of mine-type repository designs

For many years, mine-type repositories have been considered an international standard for SNF and HLW disposal purposes. MR established at a depth of 400—1,000 m are based on mature building technologies supplemented by relevant engineering structures.

Progress in the implementation of MR designs is explained by the fundamental ability in demonstrating their long-term safety in accordance with the basic requirements set forth in international and national regulations and the huge amount of research implemented in this field. Safety of mine-type repositories is based on the use of several natural (geological) and artificial (engineered) barriers in the disposal system performing relevant safety functions for various periods of time. A single barrier can perform several safety functions at a time, while their combination should provide the so-called defense-in-depth safety of the biosphere so that the safety would not depend excessively either on any single barrier or on the performance of any single function [15], [16].

Most conventional layout for MR, namely, the KBS-3 designs were developed in Sweden and adopted under deep SNF and HLW disposal designs by many countries (Figure 1). This layout is based on a most important principle providing the disposal safety and the environmental protection from radionuclides disposed of in the underground structure — a multi-barrier approach. This and other MR designs provide for the following barriers: a waste form with HLW, a metal canister for the waste form, a clay buffer between the canister and the host rock, backfill and insulating plugs of main tunnels and other underground excavations, the host rock and the geological environment as a whole, which separate the engineered safety system (EBS) from the biosphere [17].

Despite the high technical maturity level of this type of designs, in most cases, their implementation is still stalled due to high requirements to the

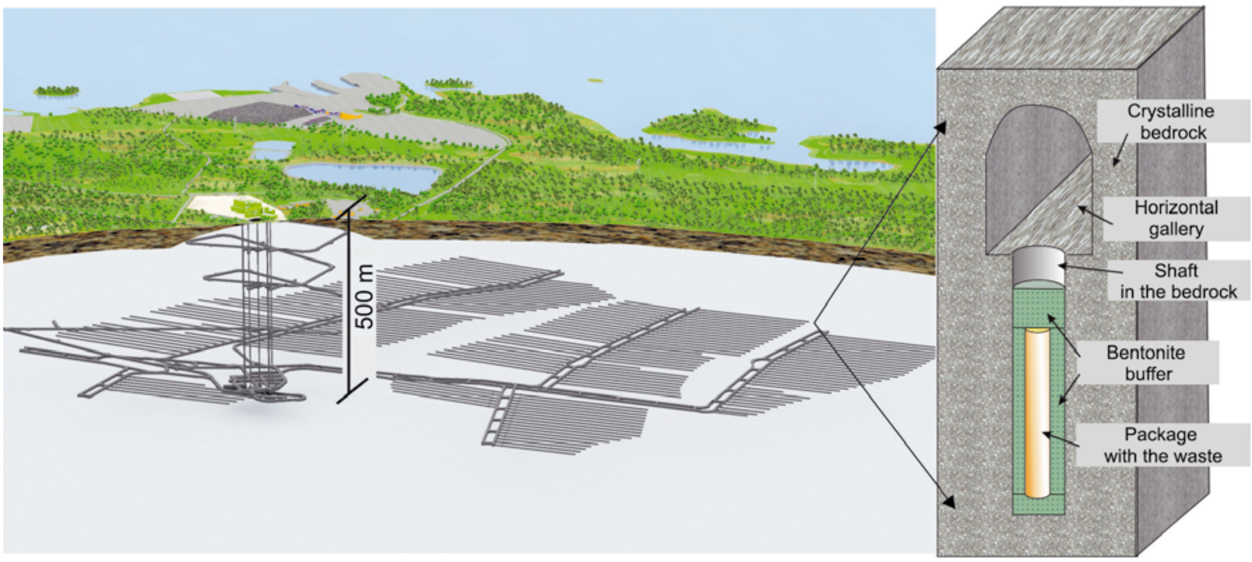

Figure 1. KBS-3 concept for SNF disposal. The general layout of tunnels in the underground facility (on the left), the inset shows the layout of a waste canister in an underground gallery (from [17, 18] with modifications)

safety assessment. The KBS-3 method has been developed by the Swedish RW operator (SKB) since the mid-1970s. Under this layout, the environmental safety in the long term is mainly provided by the EBS (a sealed container with a copper lining viewed as a key element). The licensing process in Sweden (license application was filled in 2011) is still ongoing. National regulatory authorities require more and more arguments that would demonstrate the safety. Only Finland with the disposal designs based on the same concept has managed to start the practical implementation of the project. In 2015, a license was issued to the Finnish operator (Posiva Oy) and in 2016 the construction of a SNF repository at the Olkiluoto site was started. The application for an operating license was planned to be submitted in 2021 [19].

In late 2021, activities preceding the start of underground research facility (URF) construction at the Yeniseiskiy site proposed for the future deep HLW disposal facility (MR type) were underway [20].

The deep borehole disposal concept

Drilling of boreholes reaching a depth of about one kilometer is not considered technically challenging at all. J. Biswick [21] proposed a classification of disposal boreholes by depth: more than 3 km, 1—3 km and less than 1 km categorized as deep, medium and shallow, respectively. Discussions are currently held on the concept of deep borehole RW disposal at a depth of over a kilometer.

DBD concept proposed as a worthy alternative to the MR option has always been based on the geological background that could provide natural safety of RW disposal at great depths. These advantages are illustrated by a diagram representing the changing contribution of the main long-term safety barriers (waste form, container, plugs and geological environment) to the isolation of radionuclides depending on the disposal depth (Figure 2).

At the safety assessment stage, DBD advocates rely on the geological conditions prevailing at great depths, which testify to the inherent safety of the technology in general. Dilling of such boreholes (for example, the Kola superdeep borehole reaching a depth of over 12 km, KTB Main Hole in Germany reaching a depth of over 9 km and other designs [23]) has demonstrated that groundwater occurring at a depth of several kilometers in continental crystalline basement rocks was characterized by long residence time, low flow rate and extremely low probability of their discharge on the surface if deep faults were absent. These flows had high salinity level and therefore a limited potential for vertical movement due to density stratification, thereby preventing colloidal radionuclide transport. Geochemical reducing conditions in brines, common for great depths, would limit the solubility of the main radionuclides, thereby increasing their retardation. Therefore, it seems easier to choose a proper site for borehole drilling (the key factor is the depth). The seismic safety of the siting region is considered as the main factor indicating the absence of potential risks to the overall safety of the system [24].

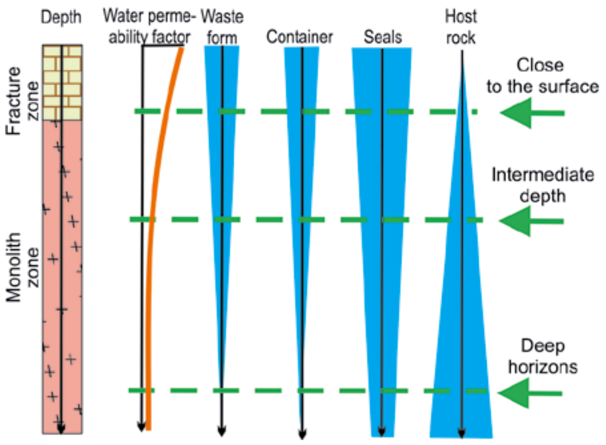

Figure 2. Differences in the contribution of the main barriers to the long-term safety of the DBD facility (waste form, container, seals and host rock) to the isolation of radionuclides depending on the disposal depth (from [22] as amended)

The economic benefits of DBD concept are explained by several factors: the boreholes can be drilled fast (compared to the mine excavation option); under favorable geological conditions, the repository can be sited directly in the close proximity to RW generation and storage sites, which, accordingly, reduces the transportation costs; the concept has low sensitivity to RW composition and heat generation level; terrorist threats are avoided; a modular strategy can be applied if needed to drill additional boreholes at different sites sometimes being remote from each other [24].

The DBD concept is considered of interest due to the general progress in borehole construction and other circumstances.

From 1970 to 1987, at the site of the Mayak radiochemical enterprise, the geological conditions of which excluded the opportunities for underground LRW disposal, certain studies were performed to evaluate potential site suitability for the establishment of a borehole repository for solidified HLW. Several investigation boreholes were drilled in the basement rocks reaching a depth of 300 to 1,200 m, which is considered as the last attempt in the implementation of the DBD concept for the HLW in Russia [25].

In 1985, a concept providing for the disposal of actinides solidified using an artificial mineral composite SYNROC in very deep boreholes was further developed by an Australian researcher A. I. Ringwood [26].

In 2003, N. Chapman and F. Gibb from the UK embarked on a discussion on the feasibility of a very deep borehole concept application as an ultimate solution to the HLW final disposal challenge [27].

In 2010, the United States halted the Yucca Mountain repository and the idea of deep borehole RW disposal gained a new impetus in this country. In 2011, employees of the Sandia National Laboratory proposed a deep borehole disposal option to the US Department of Energy (US DOE) [28]. The proposed designs that provided for a 17-inch (43 cm) borehole reaching a depth of up to 5 km are currently considered the benchmark of the DBD concept (Figure 3).

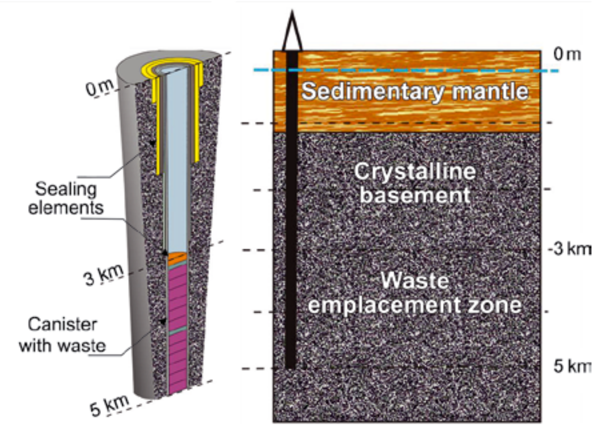

Figure 3. Basic layout of a deep borehole HLW disposal facility (from [28] with simplifications)

The safety of this concept is based on the conditions expected in the deep subsoils. For this reason, engineered barriers would play an auxiliary role at the post-closure stage of the facility. The designs developed by the Sandia National Laboratory [28] provide no requirements for the waste form. The waste containers were designed to maintain their integrity only until the borehole is sealed, which only prevents the upward transport of radionuclides released at the heat generation stage. After this period, geochemical conditions and the density stratification of liquids would be restored, therefore, the Archimedean forces would disappear triggering an upward flow that would move the radionuclides to the surface.

In 2016, the US DOE commissioned a deep borehole field demonstration program with two 5 km (3.1 mi)-deep boreholes drilled in crystalline basement rock in a tectonically stable region. At the first stage, a "characteristic" borehole with a bottom hole diameter of 8.5 inches (21.6 cm) was to be constructed. It was designed to perform certain tests to explore its physical properties and the geological environment. In the second stage, within a few hundred meters around the "characteristic" borehole, a "field test" borehole with a bottom hole diameter of 17 inches (43 cm) was to be drilled. Drilling experts agreed that although no 17-inch borehole had been drilled in the crystalline rock to a depth of 5 km, no insurmountable technical obstacle was identified that could apparently impede the construction of such a borehole. The second borehole was supposed to demonstrate the prospects of further design and operational efforts and the safety of the disposal structure. RW emplacement was not envisaged at this stage [29]. The demonstration program was put on hold already in May 2017 due to changes in the US DOE budget priorities [8].

Advances in the drilling of oil and gas boreholes penetrating hydrocarbon deposits along an inclined, up to horizontal, trajectory have given rise to designs providing for SNF and HLW disposal in the lateral sections of extended boreholes. DHD designs, discussed in detail in [11], target sedimentary strata at a depth of about 1.5 km (Figure 4a). According to the authors, clay rocks at this depth are practically impermeable. It should be noted that a huge number of horizontal drillholes have been drilled in the United States for clay reservoir hydraulic fracturing at oil and gas fields using the side drilling method. In Russia, there are some drillholes reaching record-breaking horizontal length (over 10 km). In 2017, at the Odoptu field on the Sakhalin Island, the O-5RD drillhole was drilled setting a world record for the length of its wellbore — 15,000 meters [30]. The vertical depth at the same time slightly exceeded 1 km.

A DHD concept option provides for HLW or SNF disposal in drillholes branching at a certain depth in the horizontal plane [31]. The vertical borehole is drilled to the depth of the host layer with relevant horizontal sidetracks drilled from it and secondary sidetracks that can also be drilled to increase the total capacity of the waste disposal system (Figure 4b).

The EBS design solutions implemented under this concept are basically similar to the DBD ones. The borehole is sealed with cement backfilling the annulus between the steel casing and the rock in the borehole wall. The waste, packaged into a steel canister is emplaced into a sidetrack. The only differences are associated with the disposal depth. The DBD safety principle is similar to the DHD one based on the geological environment, in particular,

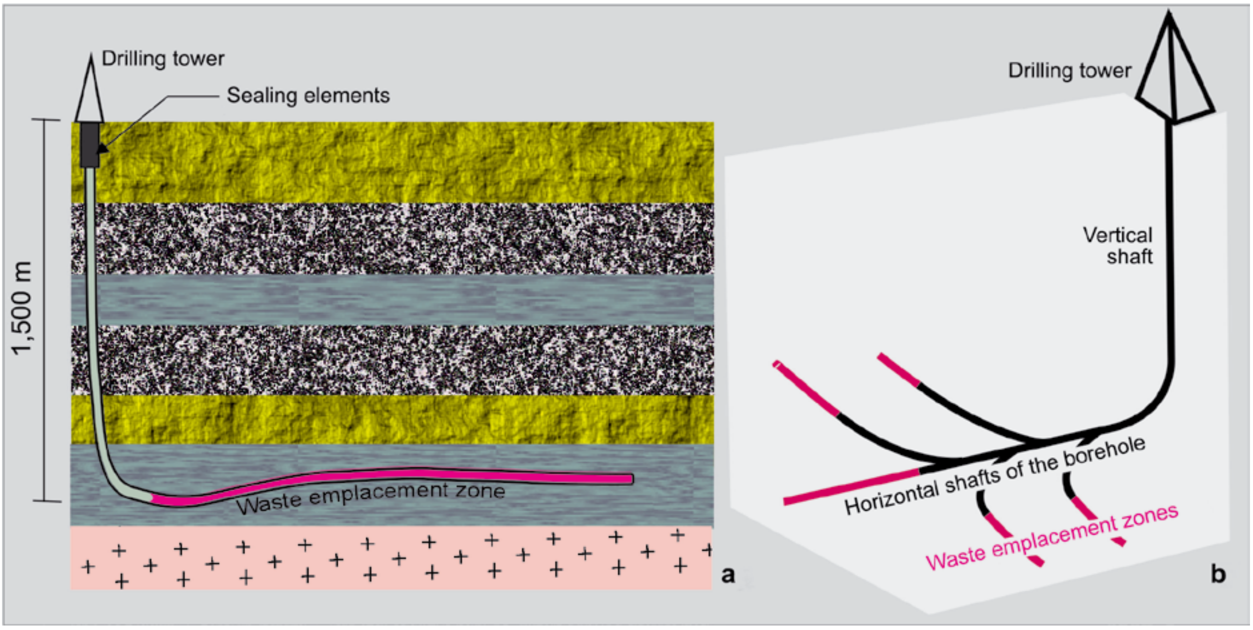

Figure 4. Layout of a HLW disposal concept in horizontal drillholes (a) option considering branching shafts (b) (from [11], [31] with simplifications)

considering that the salinity stratification, geochemistry of waters with low redox potential and plugs in the borehole should suppress radionuclide release into the biosphere [11].

According to the definition of J. Biswick [21], horizontal drillholes fall into the classes of medium or small wells. The DBD concept with its safety principles can only be implemented in really deep boreholes. With the horizontal drillhole concept proposed under DBD designs a transition from the concept of ultra-deep boreholes drilled in the crystalline basement rocks to the concept of horizontal branching drillholes drilled in the rocks of the sedimentary cover has manifested itself: in terms of geological conditions and the geometry of the excavations, their designs already differ little from mine-type repositories in plastic rocks [2].

Borehole disposal system problems

The discussion presented in [27] optimistically highlighted the “very deep borehole RW disposal” concept as a rather simple solution. However, in the future, all sorts of challenges have been faced.

The International Technical Workshop on Deep Borehole Disposal of Radioactive Waste held by the US DOE Council in October 2015, has revealed certain engineering limitations of the DBD concept related primarily to the diameter of the boreholes and the parameters of available RW packages. The latter may exceed the current technical drilling capabilities. Relatively “narrow” boreholes increase the risk of the package “clogging” before reaching the target depth.

The second challenge is related to the characterization of the disposal area. In the DBD system, in contrast to the MR, direct access of personnel to the host rock is impossible. This will obviously complicate the collection of geological information necessary for a reliable safety assessment in accordance with the existing regulations, will require the development of an adequate data collection and testing system, whereas the characterization of environmental conditions may turn out to be even more complicated than in case of MR.

The third challenge is related to the RW management policy and is of a strategic nature. In countries with developed nuclear power, it is difficult to abandon the MR approach due to the accumulated package inventory. For most RW types, available estimates regarding the DBD performance basically do not indicate any noticeable improvement in the long-term safety of this method compared to the MR one. Their disposal in deep boreholes does not eliminate the need of commissioning a mine-type geological repository for the bulk of accumulated HLW or SNF inventory. This is exactly the opinion proposed by the US Department of Energy, which has identified only a few specific RW types as potential candidates for RW disposal based on the DBD method [29]. Relevant inventory list included: canisters with cesium and strontium, untreated calcined HLW, salt waste from sodium fuel processing and some amount of SNF stored at different sites.

Similar risk levels associated with DBD method have been indicated by the global community and experts from a number of other countries. The UK waste operator (NIREX) states that the DBD concept is characterized by some aspects requiring some careful evaluation — otherwise it will remain only a potential alternative to the MR concept [32]. The latest publications of those supporting the DBD concept in the UK, on the contrary, urge its speediest implementation to address the HLW challenge [9]. Swedish specialists believe that there are still "too many gaps to address as regards the DBD option making the concept unattractive considering the current setup in Sweden." The SKB is critical of the DBD designs, but still considers it since the Nuclear Activities Act of 1984 requires a variety of research programs for nuclear waste management [33]. In Germany, since 2013, the DBD concept has been considered as an acceptable alternative option to the MR one due to the phase-out of the nuclear power. SNF inventory provides for the excavation of less than 100 deep boreholes, for example, in salt strata [34]. In recent years, employees of German organizations have been working on this project in collaboration with Australian researchers [35].

The DHD concept, especially the option providing for branching shafts at the RW disposal level, is noticeably similar to the MR concept and follows the advantages and disadvantages of all three concepts. Of particular interest is the idea of a lateral branching drillhole excavated in the clay horizons of the sedimentary cover [2]. It should be noted that part of the MR projects is also planned to be implemented in clayey sedimentary formations. One MR project in salt strata (WIPP) has already been implemented in the US [7].

The branching network of lateral boreholes is essentially similar to the network of mine excavations proposed under MR designs. Such an approach would help to explore the structure and the properties of the disposal environment to the extent necessary for a reliable safety assessment according to existing (or adapted) standards. Modern methods and tools provide fast drilling of horizontal drillholes. Unsuitable areas of the enclosing rocks can be immediately excluded from the disposal volume. This will enable accelerated commissioning of the DHD facility in comparison with the MR. A cover of interbedded waterproof sedimentary rocks and aquifers with high salinity with a total thickness of more than 500—1,000 m will provide reliable screening against vertical groundwater flows from the waste disposal horizons. The ability of clays and salts to self-seal mechanical deformations that may occur after waste disposal under external tectonic stresses is seen as an important insulating factor. It should be recognized that the DHD concept inherits some technical risks considered characteristic for the DBD concept, such as clogging of the borehole due to canister misalignment in the borehole. Operational risks may be offset by rapid drilling of new boreholes and the plasticity of the waste disposal medium.

Horizontal drillholes can accommodate waste that cannot be further retrieved and is suitable for packaging in canisters of limited diameter. According to GOST 20692 2003, which applies to cone bits for continuous drilling in loose rocks, bits with a diameter of 490 and 508 mm are mass-produced. Since the Russian Federation has a well-developed nuclear power sector and potentially suitable sedimentary strata are available throughout its territory, the DHD option may be considered promising for a number of waste streams.

As for the DBD technology, although deep borehole option is currently considered suitable for the disposal of spent radiation sources and small ILW and LLW amounts resulting from their conditioning [5, 6][1], its prospects, according to the authors, can be much broader.

Given sufficient knowledge of rocks, the achieved radionuclide containment degree at a depth of several kilometers can be significantly higher compared to the "common-type" deep geological disposal facilities for SNF and HLW located at a depth of several hundred meters (MR). However, better RW containment is somewhat offset by a significantly lower disposal capacity and some engineering issues associated with the drilling of deep boreholes of a sufficiently large diameter. In this regard, in addition to the disposal of spent sources of ionizing radiation, DBD facilities may be also used to dispose of relatively small HLW volumes that are considered challenging in case of their disposal in "common-type" deep disposal facilities due to their heat release or long-term radiotoxicity.

RW in the Russian Federation potentially suitable for borehole disposal

Particular problems are known to be associated with such RW categories as, for example, graphite from reactors or waste containing radium. Although their radioactivity levels may be relatively low, they may contain some long-lived radionuclides including ^{14}C, ^{36}Cl and ^{226}Ra [19]. Unfortunately, the borehole disposal of such a waste type as reactor graphite, the estimated inventory of which in the Russian Federation amounts to some 50 thousand m^3, is considered problematic, so simpler options are being considered [36], [37].

Borehole disposal may turn out to be a solution that could commensurate with the actual hazard

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[1] So far, the 2009 edition of SSG-1 is in force [5].

level and volume of some waste types in countries with developed nuclear power sector. Since the Russian Federation considers the transition to fast reactor nuclear power, new types of RW will appear [38]. Waste generated after minor actinide transmutation into short-lived radionuclides can be considered potential candidates for borehole disposal [39].

Considered below are the examples of some "problematic" HLW, including HLW and SNF containing 129I from new fuel cycles associated with a high burnup of fissile elements.

Iodine-129

^{129}I is the main radionuclide that is responsible for the potential exposure of the population in the long-term due to the geological disposal of SNF and HLW ($T_{1/2} = 15.7 \cdot 10^6$ years, see, for example, [40—43]). This statement is true even for vitrified high-level waste (VHLW), in which, after SNF dissolution, no more than a few hundredths of the initial activity of this radionuclide remains in place [44], [45].

High radiological hazard of RW containing ^{129}I and disposed of in deep geological repositories (DGR) is explained by minor absorbability of this radionuclide rocks. With ^{129}I half-life of about 16,000,000 years, the characteristic retardation times of several thousand years provided by DGR at depths of 400—500 m in crystalline rocks [40]—[42] and a retardation of about a million years in clayey rocks [43] may turn out to be insufficient.

In the Russian Federation, iodine released during SNF reprocessing is captured by an aluminum oxide-based sorbent impregnated with $AgNO_3$. This material can be recycled by washing the sorbent with hydrazine nitrate in an alkaline medium with silver reduction and further iodine transfer into solution. From the solution, iodine can precipitate either in the form of metal iodides or iodates (Pb, Ba, Cu, Na) and can be immobilized into cement or bitumen waste form. After the service life of the adsorption columns expires, ^{129}I must be stored directly on the sorbent. However, due to the weak bond of iodine, its carry over and release into biosphere is possible during such storage, which requires increased safety levels to be maintained during the storage or processing of a sorbent with ^{129}I specific activity of $2 \cdot 10^5$ Bq/g [46]. The same study also proposed a method providing the separation and immobilization of iodine from spent column sorbent in pressed copper powder containing copper iodide, CuI. The expected specific activity of the compound for ^{129}I was about $2.5 \cdot 10^6$ Bq/g. According to the RW classification system adopted in the Russian Federation [47], both the spent sorbent and the compound belong to Class 2 RW and shall be subject to deep disposal.

Possibly the DBD option will turn out to be even safer in case of ^{129}I-containing RW disposal in comparison with the existing designs.

Vitrified HLW from new fuel cycles

Currently, research is underway to increase the concentration of radionuclides in vitrified HLW. [48] provides the expected radiation characteristics of borosilicate glass (BSG) generated from the reprocessing of VVER-1000 SNF with a burnup depth of 50 GW day/t(U) after 7 years of cooling. Given a 20 % content of initial HLW oxides generated from the reprocessing of 1 SNF ton, 100—110 liters of BSG are produced with an energy release slightly less than 30 kW/m^3. To reduce the energy release to 2 kW/m^3, which is acceptable according to the VHLW acceptance criteria [49], some 200 years should pass, which may turn out to be unacceptable for future generations.

Similar problem arises when a decision is made on the method applied for the reprocessing of fuel returned to the Russian Federation under international agreements. One of the options proposed provides for the extraction of fissile elements used to produce new nuclear fuel and the return of the short-lived cesium-strontium fraction formed during the reprocessing back to the customer for disposal (see, for example, [50]).

This approach entails one important drawback, which is the volume and the cooling time of the returned cesium-strontium RW fraction until it would be possible to dispose of such waste in MR or in a near-surface disposal facility. Both considered cases suggest an alternative either providing for RW "dilution" to achieve an acceptable heat release level within a reasonable time or further management of concentrated VHLW with a very high level of heat release. In the latter case, the DBD option may turn to be more preferable.

Fuel cycles associated with high burnup of fissile elements

Natural uranium resources are limited. Therefore, methods seeking to produce new fissile isotopes from ^{238}U and ^{232}Th should be intensively developed, which may increase the raw material base of nuclear power by hundreds of times compared to the "commonly-accepted" approach based on ^{235}U isotope extraction from natural uranium. The future of the nuclear industry in Russia and its sustainable development is currently viewed in a transition to a closed fuel cycle and establishment of a two-component nuclear power industry [51] implying ^{239}Pu production from depleted or natural ^{238}U in fast neutron reactors.

Thermonuclear fusion geared towards new fuel production can be viewed either a supplement or an alternative option to the nuclear power development based on fast reactors. This concept was considered at the dawn of the nuclear power development [52] and has now gained some new impetus. For example, [53] states that less than 15 % of hybrid thermonuclear reactors can solve the fuel problems of nuclear power in a fundamental way.

Hybrid reactors with thermonuclear plants seen as sources of fast neutron generation for fissile nuclides in a subcritical blanket enable the use of minor actinides (MA)[2] produced from thorium, uranium and plutonium as fuel and the attainment of thresholds as regards the mixed fuel burnup depth, which is limited only by the matrix ability to retain the radionuclides. Dispersed fuel from the so-called TRISO particles (TRistructural ISOtropic) is currently considered a most stable fuel matrix: a fuel-containing ceramic core is surrounded by protective layers of pyrolytic graphite, SiC or ZrC. Particles of about 1 mm in diameter are distributed in a graphite matrix [55]. [56] reported that such a fuel can adequately retain the activity corresponding to the fission of 95—99 % of the initial heavy atoms.

Considering the given burnup depth and fragmentation nuclide generation, disposal of such SNF appears to be infeasible, whereas its disposal in conventional DGR may turn out to be unacceptable both because of the residual heat release and radiological hazard levels involved.

Conclusion

The borehole disposal concept is considered as an alternative option to the commonly recognized mine-type designs when it comes to the disposal of different RW classes. In a number of countries, theoretical and pre-design studies are actively performed seeking to develop relevant designs intended for HLW and ILW disposal at depths of 3—5 km in vertical boreholes penetrating crystalline bedrocks. Relatively recently, horizontal sections of curved boreholes penetrating sedimentary rocks at depths of 1—3 km were proposed for RW disposal purposes.

The borehole disposal concept is based on the advantages provided by the geological medium at great depths considering waste isolation, but nevertheless encounters some technical and regulatory hurdles.

It may be viewed as a preferred option in cases when the isolation of some specific RW types should be provided. In the Russian Federation, this waste may involve those containing iodine-129 and in the future — VHLW generated from new fuel cycles, including waste from fast neutron reactors and hybrid plants.

In any case, it will be necessary to overcome the limitations imposed by the borehole parameters, improve the methods applied to study the rock structures in a remote mode, as well as the technological capabilities for RW conditioning and pre-disposal management of matrix and packages suitable for borehole disposal.

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[2] In subcritical blankets, reactivity control problems associated with lower fractions of delayed neutrons in ^{239}Pu and MA as compared to ^{235,238}U are eliminated [55].

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