RW DISPOSAL SAFETY AS A FACTOR INFLUENCING THE SELECTION OF A MANAGEMENT METHOD FOR RW FROM NPP SNF REPROCESSING

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This article demonstrates how the focus placed on specific RW acceptance criteria for disposal under the Balanced Nuclear Fuel Cycle product line may contribute to a standardized SNF reprocessing product whose safe disposal, under certain conditions, may be provided even without resorting to deep geological disposal designs.

Keywords: *radioactive waste, radiochemical production, spent nuclear fuel reprocessing, radioactive waste disposal, radioactive waste fractionation, balanced nuclear fuel cycle.*

Introduction

Today, nuclear power (NP) is viewed as a steadily developing source of power generation. However, the pace and scale of its development largely depend on how the challenges faced in spent nuclear fuel (SNF) management are dealt with. Despite the apparent simplicity of the "open" nuclear fuel cycle (NFC) option either providing for direct SNF disposal in deep geological formations without its prior reprocessing or its long-term storage deferring its final disposal for decades, radiochemical SNF reprocessing offers some considerable benefits compared to these approaches, i. e., nuclear materials can be recycled providing fuel supply to NP given limited proven reserves of natural uranium.

SNF reprocessing approaches contributing to a "closed" NFC and a transition to a full-scale two-component NP are currently being widely discussed in the Russian Federation [1]. In this case, the decision-making on an appropriate fuel management flowchart is mainly based on well-established practices, which is apparently explained by the fact that regulatory requirements stipulating the principle of mandatory and safe radioactive waste (RW) disposal were adopted in the Russian Federation quite recently (in 2011), i. e. upon the enactment of Federal Law No. 190-FZ On Radioactive Waste Management and Amendments to Certain Legislative Acts of the Russian Federation [2], whereas SNF reprocessing has been running since 1970s. At the same time, given the complex nature of RW disposal processes and the associated costs, it is supposed to impact considerably (and possibly decisively) the decision-making on an optimal SNF reprocessing flowchart.

In the Russian Federation, partitioning technologies have been rapidly developing: these involve not only common extraction of fissile elements but also of minor actinides and/or alkali and alkaline earth elements, i. e., the main heat-generating

radionuclides. It is believed that, when implemented, these technologies will address not only the accumulated nuclear legacy challenges but also those related to the fuel supply of fast neutron reactors (FRs).

Their practical implementation provides for the construction of a high-capacity plant (HCP). At present time, its optimal design layout is being elaborated taking into account various partitioning options.

Therefore, in addition to a common SNF reprocessing scenario, the following partitioning scenarios are currently being considered under the envisaged HCP concept [3]:

1) **Separation of short-lived fraction (SLF) from HLW.** After the SLF (Cs-Sr) is separated, the high-level waste (HLW) raffinate is incorporated into borosilicate glass (BSG). The separated short-lived fraction is also incorporated into the BSG and, after its decay storage, is either disposed of in a near-surface or an intermediate-depth waste disposal facility (DF) or returned to the corresponding foreign SNF reprocessing customer.

2) **Separation of short-lived fraction and minor actinides.** After partitioning, the HLW raffinate is incorporated into BSG and is handed over first for storage (decay storage) and then for disposal in a deep geological repository (DGR). The SLF is managed similarly to Scenario 1. The minor actinide fraction is burnt in FR.

3) **Separation of minor actinides.** After the minor actinides are separated, the HLW raffinate is incorporated into BSG and upon completing the decay storage stage is handed over for disposal in a DGR. The minor actinide fraction is burned in FR.

4) **Separation of short-lived fraction, minor actinides and other radionuclides.** SLF and minor actinides are separated from the HLW raffinate. There are managed similarly to the scenarios above. The remaining products are separated into several fractions, incorporated into individual matrices with high isotopic capacity and after a decay storage period (if necessary) are sent for disposal.

The first scenario has been proposed under the Sustainable Nuclear Fuel Cycle (also called Balanced NFC) project run by the Rosatom State Corporation, which involves the development of a comprehensive foreign trade proposal for newcomer countries. Thus, such countries may avoid the need of building a DGR on their territory. An activity equivalent of the SNF imported to Russia for reprocessing will be returned in the form of HLW SLF to such customers.

Thus, the sustainable NFC technology offers a package of engineering solutions including a RW disposal system and conditioning of products resulting from SNF reprocessing. Based on this approach and the safety criteria for the subsequent waste disposal, the corresponding requirements for the final reprocessing products can be developed. Moreover, it offers a comprehensive service providing their packaging into multipurpose containers UKH PV (high-capacity storage packaging kits), which are dual purpose containers designed both for SNF storage and transportation and, in the future, may be potentially applied for SLF disposal in a country requesting the SNF reprocessing service.

This decision does not contradict the regulatory requirements in the field of atomic energy use. While previously, it was the Government Decree No. 1069 that was setting forth the threshold specific activities of various nuclides for the RW categorization purposes and the selection of appropriate disposal methods [4], now, in line with the amendments introduced to it [5], the threshold specific activities of short-lived radionuclides can be established in the designs of a waste disposal facility and its safety case as part of a more detailed assessment taking into account the actual characteristics of the RW and the disposal system. In other words, waste acceptance criteria for RW disposal in a specific repository are determined based on the evaluation of various elements integral to the RW disposal system in terms of their safety importance [6]. Thus, quite broad opportunities are now provided for the management of SNF reprocessing products, since the requirements for their characteristics can be developed based on the capacities of a RW disposal system.

The demonstration infrastructure being created at the Mining and Chemical Combine (MCC) site will be used for the pilot-scale testing of engineering designs developed under the Sustainable NFC product line.

This article demonstrates how a focus on individual RW acceptance criteria for disposal contributes to a standardized SNF reprocessing product whose safe disposal, under certain conditions, may not require its isolation in deep geological formations, which increases significantly the attractiveness of this process as a business service.

Principles of safe RW disposal and safety assessment of RW disposal facilities

The multiple-barrier principle relying on a system of engineered safety barriers (ESB) and host rocks stands as a generally accepted principle providing safety of waste disposal facilities. ESBs are primarily designed to contain radionuclides and reduce their releases beyond the facility's boundaries, while the function of natural barriers is to isolate humans and the environment from the harmful effects associated with RW, as well as to minimize potential human impact on the engineered barriers and the waste itself. The host rocks typically

proposed for RW disposal include thick crystalline and sedimentary rocks (such as clays), as well as salt deposits. ESBs typically involve a RW "matrix," containers (usually metal ones), layers of concrete and specially pretreated clay materials.

Under the post-closure safety assessment of a RW disposal facility, its radiation impact on the population and the environment should be forecasted and these calculated data should be compared with the established thresholds. It is important to consider all factors that produce (or may produce) somewhat considerable impact on the waste disposal system. Thus, a valid set of scenarios describing its possible evolution is developed and the consequences associated with each scenario are subject to a computational and experimental assessment.

As it comes to SNF and its high-level reprocessing products, the high heat release levels increasing the temperature of the waste disposal system should be viewed as an essential factor in the safety assessment. Heat release plays a decisive role in the selection of the final disposal concept and the characteristics of the ESBs due to its considerable negative impact on a few parameters critical for the RW disposal safety such as mechanical strength, corrosion resistance and other physical and chemical properties of ESBs.

A disposal container designed for RW with a high initial heat release (such as a SLF HLW) is viewed as the primary containment barrier. Its key function is to prevent radionuclide releases from the containers throughout the "thermal period," when high waste temperatures may deteriorate the protective properties of other ESBs. This, on the one hand, minimizes the negative impact of the RW characteristics and, on the other, increases the predictability of the disposal system and its long-term behavior. Under this approach, the safety assessment of SLF HLW disposal can be divided into two relatively independent components:

1. Thermal parameters for the disposal facility that will not compromise the ESB integrity in case if SNF reprocessing products are disposed of therein are calculated.

2. The long-term safety of the disposal facility is assessed over a period when significant heat release no longer takes place and the temperature in the disposal system drops to a level comparable to the background one typical for the site.

Thermal behavior assessment for a RWDF in case of SLF HLW (SNF reprocessing product) disposal

Temperature patterns evolving within the ESB and in the geosphere were assessed assuming various possible repository design layouts to demonstrate whether the disposal of heat-generating waste from SNF reprocessing could be judged feasible. These have been evaluated to identify the permissible initial heat release levels considering different possible SLF HLW package layouts in a borehole disposal system. It should be noted that this layout is considered feasible only in case of relatively small waste inventories subject to disposal and long-term implementation of the disposal operations, which is explained by the modular layout of the disposal cells suggesting that there is no need to operate a large number of excavations to be used in a long-term perspective. Multivariate thermal calculations were performed in two stages.

Firstly, the following layouts were specified for further modeling: single cells (to assess the ranges of variations in the geometry of the waste disposal system); linear arrangement (representing a case when the spacing between the rows of packages is many times greater than the distance between the adjacent SLF HLW packages), “grid” arrangement of SLF HLW packages with a uniform pitch (to predict thermal fields assuming a most compact layout).

Based on the results obtained at the first stage, a refined forecast was developed regarding the thermal impact of the repository on the ESB and the host rock taking into account the proposed design concept (the arrangement of the disposal cells relative to each other, mutual arrangement of heat-generating packages with SLF HLW and the non-heat-generating ESB elements in a disposal cell), which was selected taking into account the findings from the previous stage.

At the first stage, in each series of calculations, a unit specific heat release from RW at the time of its disposal was specified (conditionally 1 kW/m^3). After the distribution of temperature fields was calculated, the maximum heat release corresponding to the established temperature mode criteria was determined analytically, i. e., 100 °C for the host geological environment [7], 150 °C for the clay materials in the ESB buffer zone [7] and 450 °C for the glass-like matrix material [8]. It should be noted that these restrictions are based on internationally accepted ones but may be modified in the future when the safety functions of individual ESB elements are revised (for example, higher glass compound temperature may be adopted if it does not interfere with long-term safety functions). The repository layouts considered in the models were based on the BOSS [9] and the KBS-3V SNF disposal concepts. Loose sediments and crystalline rocks were considered as possible host rocks.

The obtained results demonstrated that under the considered disposal layouts, the heat release from the disposed waste mostly containing radionuclides

with half-lives of no more than 31 years should not exceed 2 kW/m^3 for each individual SLF HLW package not to compromise the integrity of the engineered barriers. Whereas, the average initial heat release from a SLF HLW package in a RWDF should not exceed 1 kW/m^3.

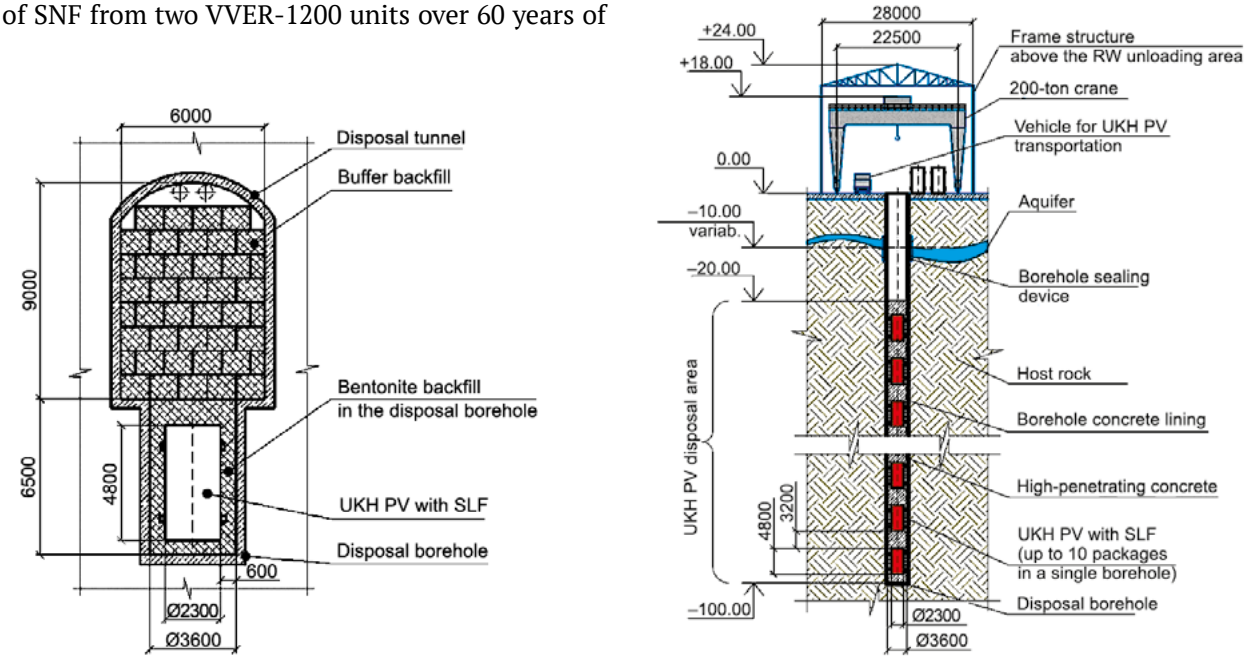
The first stage of thermal field forecasting showed that due to uncertain repository site characteristics it was quite difficult to select a particular RW disposal option. However, the KBS-3V concept (Fig. 1a) similar to the one being implemented in Sweden and Finland and the BOSS concept (Fig. 1b) were recommended as most promising ones for heat-generating waste disposal.

The KBS-3V concept was chosen as a most mature disposal option available for heat-generating waste (the Onkalo waste disposal facility in Finland). Due to the high fixed costs of accessing the underground aquifer, its implementation seems feasible in case of a relatively large number of such packages. At the same time, the borehole disposal concept can be recommended when dealing with a small inventory of heat-generating waste (up to 100 packages).

The ultimate number of SLF HLW packages handed over for disposal will depend on a few factors, in particular, the SNF reprocessing rate, the initial SLF HLW characteristics and thermal requirements for the repository being constructed, which may necessitate further reduction in the specific activity (and a proportional increase in the volume) of the RW or in the number of primary packages inside a cask transferred for disposal. Generally, based on the considered scenario assuming the reprocessing of SNF from two VVER-1200 units over 60 years of their operation and the characteristics of the forecasted SLF HLW, the number of packages should not exceed 40 pcs. Each of them is expected to contain no more than 5.4 m^3 of RW with a specific activity of up to 3,500 Ci/kg. For such a relatively small volume, it has been deemed appropriate to develop a borehole disposal option similar to the BOSS concept, which may offer some additional advantage in this case: construction of such a facility (individual boreholes) can be correlated with the rate at which the RW packages are delivered to the disposal site. It should be noted that, if necessary, their estimated number can be increased, which would require lower initial heat release from the SLF HLW but nevertheless no critical review of the disposal concept itself.

Further elaboration was focused on the requirements to the geological environment at potential repository sites: these were developed and served a basis for the developed detailed predictive models of the thermal fields generated by the heat-generating waste emplaced into such repositories. Based on the adopted repository layout and the temperatures of the geological environment and ESB, at which they implement their safety functions, the permissible initial specific heat release of the waste (at the time of repository closure) was calculated. The calculations confirmed the previously obtained limit of ~1 kW/m^3.

It is worth noting that given the initial heat release rate of 25 kW/m^3 for waste generated from SNF reprocessing, a decay storage for approximately 150 years is required to reach the target heat



a) KBS-3V *b) BOSS*

Fig. 1. SLF HLW disposal concepts recommended based on the findings from the first stage of predictive thermal calculations

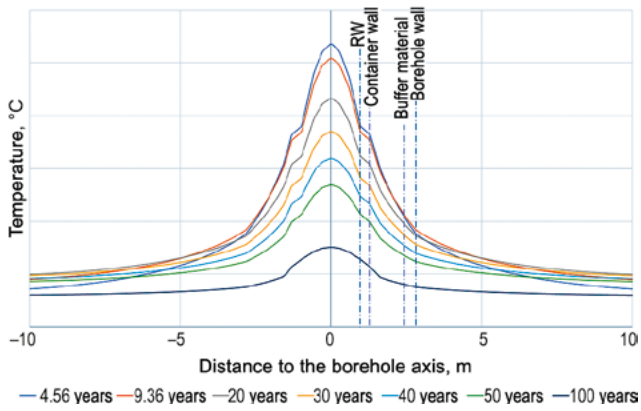


Fig. 2. Updated forecast calculations of thermal fields assuming SLF HLW disposal in a borehole repository

release rate of 1 kW/m^3, which exceeds the operational life of nuclear facilities and will necessitate an individual long-term storage facility designed for such waste. Nevertheless, the heat reduction process occurring due to the radioactive decay is predictable and the characteristics of a storage facility required for safe SLF HLW disposal will ultimately be achieved. However, in this case, construction of some additional infrastructure designed to store the large volumes of RW generated throughout the NPP's lifecycle will be required either in the customer country or the Russian Federation.

Mandatory storage of RW to reduce its heat release will ensure an acceptable temperature mode in the repository but will incur some additional costs. Multivariate calculations show that, in particular, the thermal load on the disposal system may be reduced considerably if the capacity of containers designed for SLF HLW disposal is multiply reduced or the characteristics are varied during partitioning to produce a less “energy-intensive” final product. This, in turn, would require larger capacity underground excavations for disposal driving higher EBS costs, etc. Various engineering designs are currently being developed to optimize the thermal mode in a waste repository. For example, thermal soil stabilization devices [11] may potentially reduce thermal loads on a disposal system and, consequently, allow for higher initial heat release of the waste. These devices can be implemented during repository construction in case of an intermediate-depth disposal facility, as opposed to deep repositories. However, in such a conservative area as RW disposal, such designs have not been applied to date and have not been considered in research.

It should be noted that the IAEA recommendations on minimizing the amount and activity of generated RW shall be adhered literally: "minimize taking into account technical and economic factors." Therefore, decision-making on an optimal management option for RW resulting from SNF reprocessing is a multi-criteria optimization task covering the combined costs of reprocessing, conditioning, packaging, temporary storage and disposal. Along the way, it is necessary to consider not only the economic factors but also the public acceptability of the proposed options including the “foreseeability” of relevant activities under a complete waste management cycle to avoid "imposing the burden of RW management on the future generations."

Long-term safety assessment of SLF HLW disposal

The feasibility of disposing of SLF HLW with the assumed characteristics in a near-surface waste disposal facility (at a depth of up to 100 m) was also assessed considering the long-term safety of such a repository, which was done based on predictive calculations of its potential radiation impact on the population and the environment and subsequently comparison of the calculated data with permissible exposure levels.

The preliminary safety assessment of SLF HLW disposal considered a list of 18 key radionuclides identified as radiologically significant among those potentially contained in such waste. These were selected based on their initial content in the SNF and an assessment performed to identify whether the clearance levels specified in the IAEA General Safety Requirements GSR Part 3 [12] will not be exceeded after 1,000 years (taking into account the accumulation of radionuclides in the adopted time interval due to the decay of parent isotopes). The radionuclides excluded from consideration, even under scenarios assuming unintentional human intrusion into the waste disposal system, will not pose any hazard to people after 500 years. Table 1 presents the radionuclides included into the list of radiologically significant nuclides.

Table 1. List of radiologically significant radionuclides

Target radionuclides	Impurity radionuclides		
	Transuranic radionuclides	Alpha-emitters	Fission and activation products
^{135}Cs, ^{137}Cs, ^{90}Sr	^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{237}Np, ^{245}Cm, ^{246}Cm, ^{241}Am, ^{242m}Am, ^{243}Am	^{234}U, ^{235}U, ^{236}U, ^{238}U	^{14}C, ^{63}Ni, ^{93}Zr, ^{94}Nb, ^{99}Tc, ^{126}Sn, ^{129}I, ^{151}Sm

The scenarios developed to assess the long-term safety of the RW disposal system also considered features, events and processes (FEP) of natural and man-made origin that could significantly impact

the repository safety; cause-and-effect relationships were analyzed, correlations between FEPs were established and scenarios describing radionuclide releases into the environment and human exposure pathways were determined [13].

The normal evolution scenario for a RW disposal system (hereinafter referred to as the NES), also referred to as the baseline scenario in other sources, assumes the evolution of all processes including the loss of ESB protective functions due to natural degradation upon expiration of its service life, filling of voids in the RW disposal area with groundwater, leaching of radionuclides, their transition into a dissolved form and their transport with groundwater to a discharge or water use area. Fig. 3 presents the estimates regarding the time during which the ESB may maintain their functions and the mass transfer processes may get triggered under the NES.

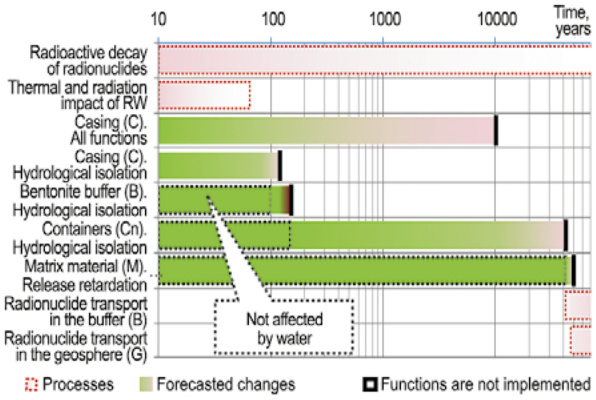


Fig. 3. Calculated time periods within which the ESBs preserve their functions and the mass transfer processes are activated under NES

Based on the forecasted radionuclide release beyond the ESB through the near and far fields of the repository, the potential dose exposure to the critical population group living and implementing economic activities in its immediate vicinity was estimated.

Based on analyzed external natural and man-made impacts (including the catastrophic ones), a set of possible scenarios were identified for the repository evolution. These were grouped into seven alternative scenarios (AS) that were considered in the safety assessment of the RW disposal system, including:

AS1. Destruction of "robust" ESBs, for example, due to a seismic impact of beyond-design-basis intensity 100 years after the repository's closure, i. e., after the stage of active institutional control is completed, which, in addition to monitoring, includes recovery or compensatory measures in the event of an integrity damage.

AS2. Change in the position (lowering) of the phreatic aquifer due to climate change or human activity 100 years after the repository's closure.

AC3. Accelerated degradation of the buffer material due to interactions between groundwater, elements of the ESB system, increased thermal exposure from RW or violations during buffer barrier construction (selection of an unsuitable material, poor compaction, pressing, backfilling, etc.).

AC4. Accelerated degradation of the container material or other damage to the integrity of the RW packages.

AC5. Loss of certain safety functions by the RW disposal system due to human activity in the near-surface region (e.g., road construction) inflicting damage to the upper portion of the casing and the material filling the upper portion of the boreholes.

AC6. Decreased sorption properties of the host geological environment with respect to radionuclide transport.

AC7. Localized unintentional human intrusion into the disposal system, i.e., drilling of a borehole potentially affecting the matrix material (RW), compromising the integrity of the packaging and buffer layer (it is assumed that the initiating event occurs after the passive institutional control is lost, i.e., lack of knowledge on the repository site).

Thus, maximum potential exposure on the population due to SLF HLW disposal was determined based on predictive calculations (Fig. 4).

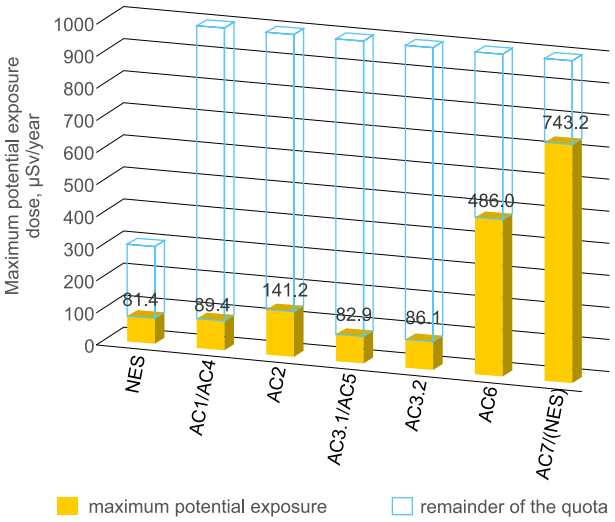


Fig. 4. Forecasted maximum dose exposure on the population assuming various evolution scenarios for the SLF HLW disposal system

The preliminary long-term safety assessment demonstrated that the repository safety is provided for the entire period within which the radionuclides contained in the disposed SLF HLW potentially remain hazardous taking into account possible

negative assumptions and those made under all the evolution scenarios considered. The total potential public exposure due to the disposal facility did not exceed:

- 100 μSv/year under normal evolution scenario;
- 500 μSv/year under alternative scenarios taking into account all most unfavorable evolutionary factors;
- 1 mSv/year under alternative scenarios involving unintentional human intrusion into the RW disposal system.

Based on the characteristics of the SNF reprocessing products and the preliminary long-term safety assessment, minor actinides require the highest treatment degree (approximately 10,000 times) to enable safe disposal of SLF HLW in a disposal facility at a depth of up to 100 m. Table 2 summarizes the limitations imposed on the ultimate content of uranium isotopes and transuranic elements in the SLF HLW inventory based on the safety assessment.

Table 2. Limits imposed on the radionuclide inventory of SLF HLW in case of its disposal at a depth of up to 100 m

Isotopen	Specific activity of SFA (at the time of reprocessing), Bq/t	Required reduction factor for the specific activity of uranium isotopes and minor actinides in the RW resulting from the SNF reprocessing relative to fuel in a near-surface repository
^{234}U	$5{\cdot}10^{10}$	$4{\cdot}10^{3}$
^{235}U	$4{\cdot}10^{8}$	$2{\cdot}10^{4}$
^{238}U	$9{\cdot}10^{9}$	$1{\cdot}10^{2}$
^{237}Np	$2{\cdot}10^{10}$	6·10
^{238}Pu	$4{\cdot}10^{14}$	$1{\cdot}10^{4}$
^{239}Pu	$1{\cdot}10^{13}$	$7{\cdot}10^{4}$
^{240}Pu	$3{\cdot}10^{13}$	$4{\cdot}10^{4}$
^{241}Pu	$4{\cdot}10^{15}$	2·10
^{242}Pu	$2{\cdot}10^{11}$	1·10
^{241}Am	$9{\cdot}10^{13}$	$1{\cdot}10^{4}$
^{242}Am	$6{\cdot}10^{11}$	3·10
^{242m}Am	$3{\cdot}10^{12}$	$2{\cdot}10^{2}$
^{243}Am	$4{\cdot}10^{14}$	$3{\cdot}10^{4}$
^{242}Cm	$1{\cdot}10^{11}$	$8{\cdot}10^{0}$
^{244}Cm	$5{\cdot}10^{10}$	$1{\cdot}10^{2}$
^{245}Cm	$4{\cdot}10^{8}$	6·10

Conclusion

This article examines the key aspects associated with the decision-making on an appropriate management method for RW resulting from SNF reprocessing which was done based on the example of the Sustainable Nuclear Fuel Cycle concept taking into account relevant safety requirements for RW disposal.

The conducted studies demonstrate that the heat release from the RW impacts considerably the repository designs and governs the requirements for the ESB depending on a particular host rock environment and the site proposed for repository construction. It has been established that, to ensure an acceptable temperature mode in a disposal system, the heat release from the RW at the time of its disposal under the conditions considered in this study should not exceed 1–2 kW/m^3. At the same time, work is still in progress on some promising engineering designs that are supposed to increase the permissible heat release, for example, by introducing thermal stabilization devices into the disposal system.

A scenario-based long-term safety assessment confirmed that disposal of SLF HLW in near-surface disposal facilities is feasible provided the adherence to the requirements on the content of long-lived radionuclides and minor actinides in particular. In addition to target isotopes, transuranic elements contribute in an essential way to the potential radiation impact, thus, they shall be extracted to a sufficiently high (and technologically achievable) level during SNF reprocessing.

The study showed that a comprehensive approach is required to manage the RW from SNF reprocessing, which should consider not only the technological aspects of reprocessing but also the requirements for its safe disposal. An optimal RW management flowchart should be selected based on a multi-criteria analysis that would also address the economic factors and the social acceptability of the RW management strategy while unconditionally meeting the safety requirements.

It appears technologically feasible to abandon the deep disposal concept in case of SNF reprocessing products subject to a return to the SNFC customer country. At the same time, the requirements of "not imposing an undue burden on future generations" and the social acceptability of a strategy selected to manage the RW from SNF reprocessing necessitate further search for some promising engineering designs that would be able to cope with higher permissible heat release levels from the RW subject to disposal.

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Bibliographic description

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