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OPPORTUNITIES FOR CONTROLLING BOROSILICATE GLASS PARAMETERS DURING VVER-1000 SNF REPROCESSING AT PDC MCC

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The paper considers the ways in which the parameters of RW 1 class generated as the result of WWER-1000 SNF reprocessing can be arranged for the purposes of its disposal. This type of SNF will be reprocessed at the pilot demonstration centre at FSUE "MCC" with the generated waste being packaged into canisters with borosilicate glass. Taking into account the basic technology providing for the production of RW packages with heat generation capacity of about 26 kW/m³ substantially exceeding the disposal criteria (2 kW/m³), the authors considered various scenarios for PDC and DRWDF evolution. An approach was also suggested allowing to arrange SNF batches for reprocessing so that the resulting RW could comply with the requirements.

Keywords: *spent nuclear fuel (SNF), radioactive waste (RW), borosilicate glass, RW disposal, deep radioactive waste disposal facility (DRWDF), heat generation*

Introduction

The need for fractionating high-level radioactive waste (HLW) generated during the reprocessing of spent nuclear fuel (SNF) with cesium and strontium fractions being segregated from the waste prior to its incorporation into borosilicate glass-like matrix (BGM) is considered as an issue being quite actively discussed at the moment. Cesium and strontium fractions should be separated from the waste in order to reduce residual heat generation and eliminate the need for the long-term pre-disposal storage of the vitrified radioactive waste [1]. The requirements for the characteristics of the spent fuel reprocessing products are closely related to the conditions of their subsequent disposal.

Proposals on preliminary fractionation were based on the design characteristics of the BGM evaluated given for the following conditions of spent fuel assemblies (SFAs) reprocessing: burnup of 50 MW day/kg U and storage time of at least 7 years. However, under current PDC project, fractionation technology was not supposed to be applied at all solely suggesting the development of fractionation technologies in the research chambers of the PDC (first start-up complex). Issues associated with the HLW generated from SNF reprocessing and waste characteristics revolve around relevant tasks associated with the subsequent waste disposal.

Regulatory framework ensuring the safety of RW disposal in Russia will evolve [2] with restrictions on the heat generation set as fundamental criteria for the vitrified HLW being subject to disposal. These restrictions result from two fundamental

factors — temperature and related stress-strain state of the rock mass and the operation modes of the safety barriers. The first restriction, in addition to the heat release requirements, is partially addressed by setting up a more scattered layout of the packages within the rock mass; whereas the second one, in addition to the same layout solutions, also involves certain restrictions on heat resistance imposed on the construction materials proposed for the engineered safety barriers construction. In both cases, with increasing heat generation, the disposal cost grows (Figure 1).

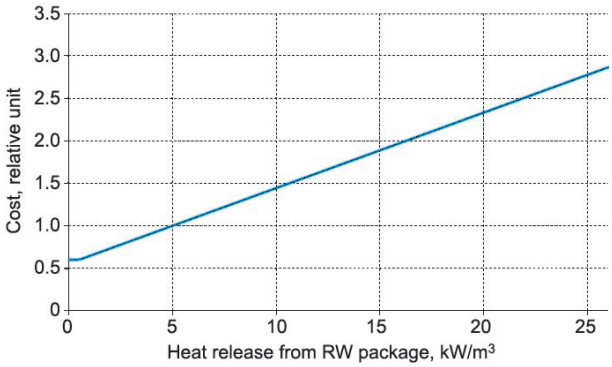

Figure 1. Dependence between the RW disposal cost and its heat generation

Provisions of federal norms and rules in the field of atomic energy use [3] specify the requirement on the heat release from RW packages that should not exceed 2 kW/m^3 which is fully consistent with the globally accepted criteria (Table 1). For aluminophosphate glass (APG) accumulated at FSUE PA Mayak, the existing design disposal solution suggests a ratio of 1:7—1:8 for RW and packaging volumes correspondingly.

Table 1. SNF and HLW acceptance criteria based on heat release

Country	Acceptance criteria based on hear generation
Sweden	1,700 W/container
Finland, BWR fuel	1,700 W/container
Finland, VVER fuel	1,370 W/container
Finland, PWR fuel	1,830 W/container
France	500 W/package
USA (WIPP)	300 W/package
Switzerland	1,500 W/package

Considering the issues associated with the heat released by vitrified HLW, it should be noted that the opportunities for balanced SNF reprocessing (by mixing spent fuel assemblies with different burnups, cooling times, etc.) at PDC, the heat produced by the resulting waste (for the first 20 years at least), allows to avoid additional segregation of heat-generating fractions due to wiser accounting (use) of the following circumstances:

- correct interpretation of disposal requirements;
- targeted selection of spent fuel assemblies for reprocessing;
- efficient use of the existing and emerging infrastructure for SNF and HLW storage.

Present article does not consider the issues associated with HLW fractionation and transmutation of minor actinides to reduce the radiotoxicity of the disposed HLW which can be to some extent explained by the clash of opinions expressed by the authors regarding its need. We hope that a particular paper will be published in the Radioactive Waste Journal to present a systematic overview of HLW fractionation technologies taking into account the entire cycle of secondary RW management.

Effective use of infrastructure for RW storage, processing and disposal

Construction of an underground research laboratory (URL) is currently underway in the Russian Federation. The strategy for DRWDF establishment [4] and relevant R&D program has been developed [5] serving a basis for the development of specific steps enabling to plan BGM disposal in this facility suggested as a potential location for waste emplacement.

This article evaluates the feasibility of arranging a BGM stream with the heat release characteristics required to ensure the safe disposal for a specific disposal period set for the first batches of SNF being reprocessed at PDC MCC.

The pilot demonstration center is designed to refine promising technologies, prototypes of equipment and SNF reprocessing practice. The design capacity of the PDC will amount to 250 tons of SNF per year with the start of its operation scheduled for 2021. PDC designs suggest that WWER-1000 SNF reprocessing results in the generation of vitrified HLW with a maximum allowable heat release of no more than 26 kW/m^3 while the specific waste generation amount will account for some 0.12 m^3 per one tone of SNF.

Two storage facilities are to be constructed inside the PDC technological unit to enable temporary storage of BGM: given the design capacity of the center, they will receive the waste for 10 years. In addition, "wet" and "dry" units designed for WWER-1000 SNF storage were constructed and are being operated at FSUE "MCC" site. The accumulated stock of "cooled" fuel seems to be a quite valuable

resource, since its joint reprocessing with "fresher" fuel allows reaching the target levels of heat release during waste disposal.

Efforts on DRWDF establishment are being implemented in accordance with the approved Strategy [4] stipulating that an underground research laboratory should become operational at least until 2030 followed by a final decision on the construction of RW class 1 and 2 disposal facility. First of all, the DRWDF will accommodate aluminophosphate glasses accumulated at FSUE PA Mayak site. In this regard, disposal of BGMs produced by the PDC may take place no earlier than in 2050.

The above situation allows to evaluate optimal ratios for SNF batches according to their burnup levels and cooling times so that by the time of BGM handover to DRWDF, general and specific acceptance criteria are met, including those associated with heat release.

Below is given an example of an approach on the selection of spent nuclear fuel batches allowing to comply with general requirement on the non-exceedance of the heat generation criteria for HLW disposal.

Targeted selection of spent fuel assemblies for their reprocessing

In the first decades of KhOT-1 operation, SNF was stored at Novovoronezh, Balakovo and Kalinin NPPs (Figure 2). Following reactor operations, the burnup rates were increased. This trend more clearly revealed itself at the NNPP (Figure 3), for which the burnup of 40 GW·day/t U or more was achieved following a ten-year service life.

SFA passport data was used as initial data for the target sampling: core unloading data, date of SFA delivery to MCC site, burnup, heat emission from the spent fuel assembly (SFA) estimated at the time of its loading for transportation, and the date of the evaluation itself.

When solving SNF reprocessing challenges one should account for the further management stages associated with the generated RW. Therefore, it seems logical to consider the interrelated scenarios for the development of PDC and DRWDF.

The forecast on WWER SFA accumulation was made in accordance with the roadmap of NPP unit shutdowns. Replacement of RBMK-1000 shutdown capacities is offset by commissioning of WWER-1200 reactor units (similar to Leningrad and Kursk NPPs). Another point taken into account in the forecast, is the fuel cycle length of 3 years with annual unloading of some 20 tons of SNF per year. Figure 4 shows the forecast for the accumulation of spent fuel assemblies based on a moderate

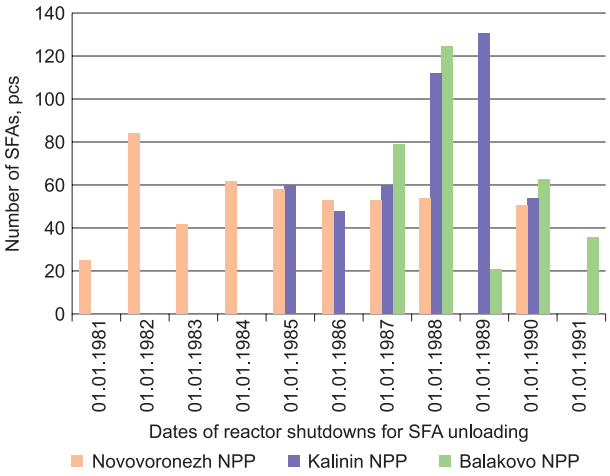

Figure 2. Breakdown of SFA number delivered to MCC from Novovoronezh NPP, Kalin NPP and Balakovo NPPs by years

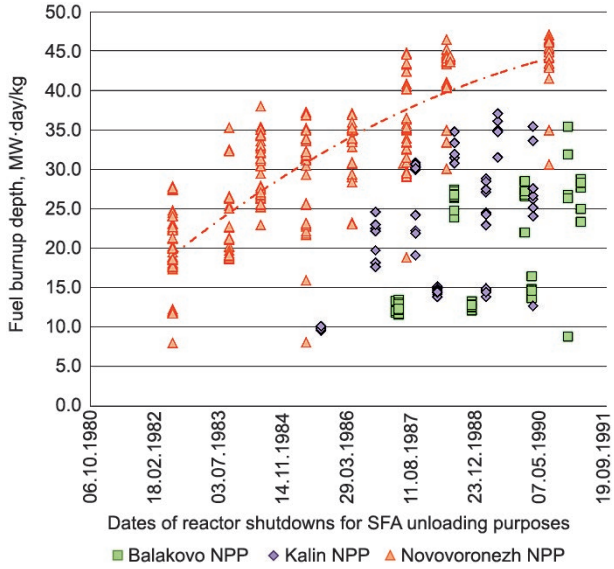

Figure 3. Distribution of SFA by burnup levels depending on the transportation date

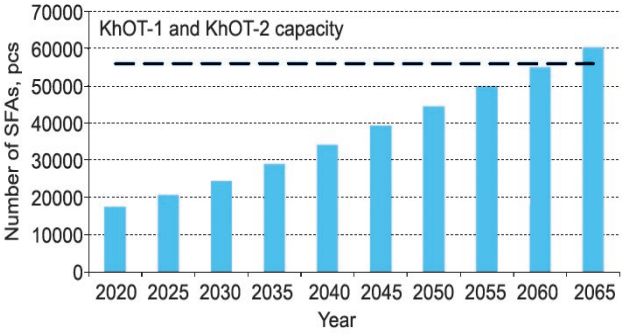

Figure 4. Forecasts on SFA accumulation in storage facilities

scenario for the commissioning of spent nuclear fuel reprocessing capacities.

In all the cases considered, total useful capacity of KhOT-1 (in case of its long-term operation)

and KhOT-2 is to be exhausted at the turn of 2060. When choosing a reprocessing tactic, it should be stressed that the volume of the SNF pending reprocessing tends to increase with the average cooling times decreasing at a slow pace.

SFA processing tactics

Beforehand let's estimate the maximum heat release by BGM package at the time of its disposal given the design documentation suggesting the reprocessing of two spent fuel assemblies (~ 1 t of SNF) with the volume of resulting BGM of 0.12 m³. Since detailed information on the design of the package in which the BGM is to be stored is missing, let's state conservatively a correction factor of 2.5, since its value for aluminophosphate glasses seems to be much higher. Under these assumptions, the maximum heat release from RW package at the time of its loading into the DRWDF should not exceed 600 W.

The most straightforward approach to the development of spent fuel reprocessing schedule provides for a staged extraction of accumulated SFAs in a chronological order. It is clear that such a staged SFAs reprocessing will result in some undesirable effects:

- it will be necessary to store relatively cold glass on the surface, as well as the glass considered as being insufficiently "cold" for disposal purposes;
- in the first two decades, all spent fuel assemblies accumulated by the time of PDC commissioning (2021) should be reprocessed, and for most cases, heat release from BGM at the time of its receipt will be in the range of acceptable values;
- as a result of "fresher" SFAs reprocessing, BGM with high heat generation rate will be produced requiring additional long-term storage.

To forecast SNF/BGM heat generation rates for a long-term perspective (40—70 years), relevant evaluations have been done (given complete absorption of the energy coming from all emitted particles, including gamma radiation) using the TRACT software package [6] (Figure 5). On the whole, the calculation results correlate with the data presented in the reference and safety guides [7, 8].

Calculated data shows that to reprocess assemblies with the maximum burnup of the SNF accumulated to date (44 MW·day/kg U), the preliminary cooling time shall account for ~ 60 years. This confirms the following thesis: SFAs reprocessing in a chronological order results in the accumulation of "hot" glass.

To avoid such situations, it is necessary to build a balanced system enabling to arrange SFA batches for reprocessing with due account of PDC goals as regards annual SNF reprocessing amounts. Heat

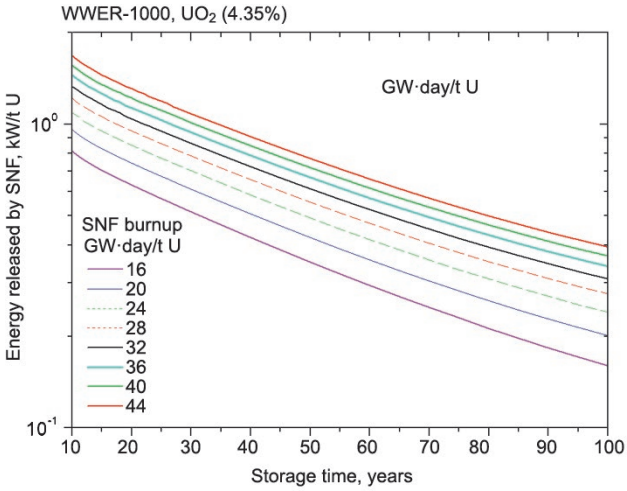

Figure 5. Changes in SNF energy release rates during the long-term storage given various burnup levels

output from the BGM at the moment of its emplacement into the disposal facility should account for the key indicator.

The boundary conditions should be identified to enable balanced heat release by BGM packages at the time of their emplacement into the disposal facility:

$$W_{\min} \le \sum_n \sum_i {}^nA_i \cdot P_i \cdot e^{-\lambda_i \left(t_{empl} - t_{rep}\right)} \cdot w_i \le W_{\max},$$

where: ${}^nA_i$ is the activity of the i-radionuclide at the time of n-SFA reprocessing; P_i stands for a coefficient accounting for the changing activity of the i-radionuclide during SNF reprocessing (extraction, process losses, etc.); λ_i is the decay factor for the i-th radionuclide [1/year]; t_{empl} is the year of BGM package emplacement into the repository; t_{rep} — year of SFA batch reprocessing; w_i — heat release per one decay of the i-radionuclide [W/dec]; $W_{\min}$ — minimum heat output at the moment of BGM package emplacement into the repository determined based on the emplacement conditions [kW]; $W_{\max}$ — maximum heat release at the time of RW loading into the repository identified based on regulatory requirements [kW].

$$W_{\max} = W_{pr} \cdot V_{RW} \cdot k \cdot \frac{n}{2},$$

where W_{pr} accounts for the maximum heat release per unit volume [kW/m³]; V_{RW} — radioactive waste volume [m³]; k — coefficient accounting for the changes in RW volume due to packaging; n is the number of reprocessed SFAs.

To demonstrate the feasibility of such an approach, a most optimistic scenario should be considered:

- SFA reprocessing will be started in 2021 with BGM disposal operations started in 2050;
- annual amount of SNF reprocessing at PDC after the stationary operational mode is attained will account for 400 tons;
- amount of BGM emplaced into the repository will account for 100 tons;
- a batch of SFAs subject to reprocessing includes 2 SFAs (given that 0.12 m^3 of BGM is produced out of 1 ton of SNF, i. e. one package).

618 of purposely selected SFAs are to be reprocessed so that each year 100 tons of BGMs with the required heat output capacity could be disposed of in the repository.

For the sake of convenience, one should breakdown the SFA operating time into decades with the SFA reprocessing process being arranged in such a way that over ten years of operation the PDC would reprocess not only the SFAs accumulated over the first 10 years, but also the fresher ones. In this case, the total SNF/BGM cooling (storage) time would account for some 40—70 years depending on the period of SFA formation (Table 2). Under this scenario, BGM generated in 2021 will be disposed of in 2050.

Table 2. SFA/BGM storage time

Year of SNF generation	Start of SNF reprocessing	Pre-reprocessing storage, years	Start of SNF emplacement into the repository	Total SNF (BGM) storage time prior to disposal, years
1981–1990	2021	40	2050	70
1991–2000		30		60
2001–2010		20		50
2011–2020		10		40

According to inventory data, during the first decade (1981—1990), a total of 1,270 SFAs from WWER-1000 power units were handed over to MCC. To enable their uniform reprocessing, annual batches should be arranged according to relevant burnup levels. Table 3 presents an annual batch subject to reprocessing with relevant data being identified based on general distribution of SFAs amounts according to their burnup levels (Figure 6). Each SFA batch accounting for other operational periods will amount to 164 pcs.

Table 3. Distribution of annually reprocessed SFAs pertaining to the first operational period (1981-1990)

SNF burnup range, MW day/ kg U	Number of SFAs annually sent for reprocessing, pcs
0–20	41
20–30	40
30–40	34
40–50	12

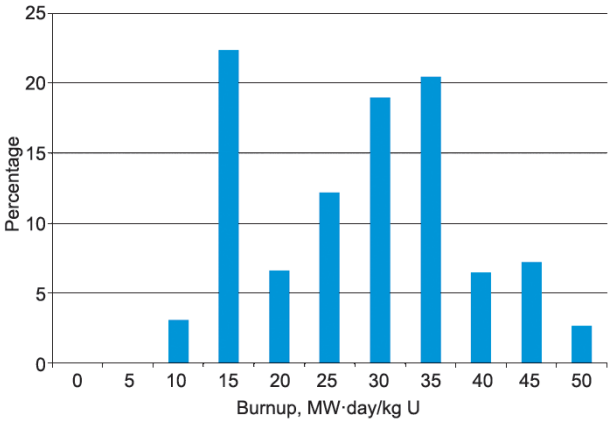

Figure 6. Distribution of accumulated SFAs by burnup level during the first decade of WWER-1000 NPP operation

The possibility of implementing such a targeted approach in principle can be demonstrated using the example of the first SFA batch sent for reprocessing. One should conservatively assume that a batch of 164 SFAs with the shortest cooling time (2011) consists entirely of the assemblies with a maximum burnup of 44 MW·day/kg U. To enable their reprocessing, it would be necessary to arrange SFA batches with the holding times given in Table 4. Even taking into account the conservative assumptions stated above, it seems clear that the required batch can be in fact arranged for reprocessing, i. e. a possibility in principal exists allowing to arrange such SFA batches on an annual basis.

Table 4. Pre-disposal storage time for SFAs with different burnup levels allowing to arrange SFA batch for reprocessing

Burnup, MW-day/kg U	Minimum SFA storage time, years
8	Less than 7
12	Less than 7
16	40
20	50
24	60
28	65
32	75
36	80
40	85
44	90

The proposed approach should be tested using actual data on the accumulated SFA covering other operational periods of the power units (1991–2018) and additional possibilities for LRW averaging prior to its vitrification. After such updating, it seems feasible to use this approach in case of a multivariate analysis with uncertain initial conditions,

including various scenarios for RW emplacement into the repository (start of operations, amounts of RW subject to disposal, etc.), SNF reprocessing volumes, etc. This will allow avoiding unfavorable generation scenarios for RW with beyond-design basis radiation characteristics.

At the same time, it seems clear that additional circumstances may arise requiring out-of-turn reprocessing of some assemblies, including those characterized with relatively short cooling time and high burnup. Therefore, it is necessary to develop the corresponding component of an automated process control system (APCS) enabling the optimization of BGM parameters under particular process conditions.

Reliability of the initial burnup data seems worth considering as a separate topic. Selective tool control is considered advisable at least with the examples of such installations being considered as well-known [9, 10].

Pre-disposal storage of BGM

The complex nature of the development process associated with the establishment of PDC and DRWDF makes the task of just-in-time operation (generation/disposal) beforehand unsolvable. Moreover, decay storage practice enabling to reduce the heat output coming from the waste is already seen as a common practice. Under PDC project, a process flow chart has been adopted providing for BGM storage followed by its shipment away from the storage facility site. A reloading machine (RM) retrieves the package from corresponding storage cell using specifically set coordinates and delivers it to control station where it undergoes the final inspection, i. e. external inspection, identification number control, compilation of supporting documentation using data from SGUK RV and RAO. Subsequently RM enables BGM package loading into a transport trolley and its transportation along the existing transport corridor to the canister supply chamber (CSC) pertaining to HLW vitrification unit (unit number 19). Following its final inspection, the package moves through the CSC gate and is discharged into onsite "armor-type" shielded container and on the platform of loading-unloading machine (LUM). LUM together with the BGM package is handed over to PDC receiving unit (unit 05) being subsequently transferred to WWER-1000 "wet storage" compartment located in building number 1. Further, BGM package can be transferred to the process storage facility in keeping with WWER-1000 SNF transfer flow chart providing for package reloading from the "wet" storage facility to the "dry" one (to reduce heat output to the required levels), or according to the wet storage system flowchart — may be for instance packed into TUK-13 allowing its further transportation by rail.

Optimization and reduction of conservatism

The paper does not consider a number of circumstances that may affect final design and engineering solutions applied. An attempt was made to enable their qualitative and quantitative evaluation.

K_1 accounts for the factor conditioned on the average inclusion of HLW oxides into the BGM. For many process reasons, reduction of HLW inclusion into the glass matrix is possible resulting in a decrease of glass activity and, ultimately, in the increase of its volume and decrease in the heat output (by 10—50 %).

K_2 accounts for the factor making allowance for the ratio between BGM volume in the package and its total volume. Here it is assumed as being equal to 1:2.5 (unlike APG packages with a three-fold higher factor).

K_3 accounts for vitrified HLW loading density coefficient. In principle, a discontinuous loading scheme can be arranged with neighboring disposal chambers being filled with a time interval of 15—20 years. K_3 may fall within the range of 0.8—0.9.

K_4 accounts for the factor associated with the conservative nature of burnup and heat release calculations. All burnup and burnup-based heat release assessments were performed by means of calculation. Operation of "wet" and "dry" SNF storage facilities has solely demonstrated that these values were not exceeded. Instrumental control of these parameters will probably give a conservative value of 0.9—0.95. Corresponding measures allowing for such instrumental control of nuclear-physical and thermal SFA parameters should be envisaged to be implemented at MCC.

Conclusion

The paper focuses on HLW generated from the reprocessing of accumulated SNF amounts already stored at FSUE MCC site. Relevant task of arranging BGM packages considered as being suitable for their safe disposal in the repository according to the heat release parameters with the start of disposal operations in 2050 and 2060 can be addressed by mixing the batches of SNF with different cooling times and burnup levels. For this purpose, APCS components should be successively developed.

Early PDC operation should be expediently limited to the glass production being considered suitable for disposal from 2060. Such an operational mode will allow further saving of SFAs with low burnup levels and long cooling times enabling the

production of colder glass, if necessary, and in limited amounts.

Regular review of the main scenario conditions, in particular, the one based on the results of early PDC operation, R&Ds performed in URL and the decisions associated with DRWDF development is considered advisable.

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Bibliographic description

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