

STRATEGY FOR THE FRACTIONATION OF HLW FROM SNF REPROCESSING

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The paper considers the main prerequisites of the fractionation strategy for HLW from SNF reprocessing. It analyses the composition of HLW resulting from SNF reprocessing taking into account the requirements for the quality of the glass compound and the criteria forming the basis of the classification system for solidified radioactive waste. The paper evaluates the opportunities for renouncing the idea of deep HLW disposal. It proposes basic HLW fractionation options with an assessment of their feasibility considering the engineering tools available. For the proposed strategies, the paper evaluates the volumes of solidified RW fractions and the RW disposal cost. Based on the calculations performed, it also presents the postulates of the fractionation strategy.

Keywords: spent nuclear fuel, reprocessing, high-level waste, fractionation, minor actinides, radioactive waste.

Introduction

Official IAEA data [1] show that since 1990, the spent nuclear fuel (SNF) inventory unloaded from nuclear reactors saw a four-fold increase. Over the same period of time, the amount of reprocessed SNF has almost doubled. SNF inventory held under long-term controlled storage is growing rapidly. The global trend for large-scale SNF reprocessing, which emerged in the 1960s–1970s, has practically tailed off. Large part of European facilities and all SNF reprocessing facilities in the US have been closed, while industrial reprocessing in the UK has practically stopped. Some large-scale plans are advanced in large Asian countries — India, Japan and China — but the actual commissioning dates keep getting pushed back. Today, industrial SNF reprocessing prospects look rather optimistic only in France and Russia. Such changes in the above trend

can be explained, on the one hand, by the complexity of the reprocessing technology itself and, on the other hand, by the fact that no option is available for the management of high-level waste (HLW) generated during SNF reprocessing that could be considered acceptable from the cost-quality perspective.

Basic prerequisites for the HLW fractionation strategy

Most of well-known options applied in the industrial SNF reprocessing (PUREX process options) provide for the separation of uranium, plutonium, neptunium and sometimes accompanying technetium as target elements. In turn, the vast majority of HLW fractionation options, with the fractionation nowadays often considered as a stage either

associated with the main reprocessing process or intersecting it, involve the separation of minor actinides (americium, curium and neptunium) and/or fractions of alkaline and alkaline earth elements, i. e., the main heat generating radionuclides [2].

Available economic estimates indicate an insignificant contribution of fractionation to the total costs at the final stage of the nuclear fuel cycle (NFC) against the background of costs associated with conditioning, controlled storage and disposal of radioactive waste (RW) [3]. Therefore, these stages in particular, i. e., the storage and disposal options selected for the conditioned RW should be considered in the first place in the fractionation strategy development.

Federal Norms and Rules in the Field of Atomic Energy Use. Collection, Processing, Storage and Conditioning of Liquid Radioactive Waste. Safety requirements (NP-019-15) is seen as the main regulation discussing the characteristics of conditioned RW generated from SNF reprocessing in Russia. If a glass-like compound is chosen as a waste form for the conditioned HLW, one should be guided by the amendments introduced to NP-019-15 in 2021 presenting the main quality indicators of this material containing RW [4] (Table 1).

Table 1. Main indicators for the quality of the glass-like compound

Parameter	Value
Mass fraction of α -emitters	Not more than 0.2%
Resistance to β -, γ -radiation	Not less than 10^8 Gy (for 10,000 years)
Resistance to α -radiation	Not less than 10^{18} α -decays/cm ³ (for 10,000 years)

The requirements in Table 1 are currently applied both to aluminum-phosphate and borosilicate glass.

At the same time, back in 2016, a draft amendment to NP-019-15 was published proposing to increase the permissible absorbed dose for β -, γ -radiation for borosilicate glass to 10^9 Gy (for 10,000 years) [5]. Experimental data have recently been published confirming that borosilicate glass of a base composition (accepted for HLW vitrification by the Pilot Demonstration Center of FSUE MCC) retained its quality at β -, γ -radiation doses of up to $3.07 \cdot 10^9$ Gy [6].

If one considers the radiation resistance indicators as certain proven thresholds, i. e., the maximum permissible dose loads for a given waste form, it seems obvious that the presented limits restrict the minimum volume of vitrified RW generated from SNF reprocessing. Any other interpretation seems incorrect, since at higher, i. e., unproven,

radiation loads, the characteristics of this waste form may no longer satisfy the safety requirements. In other words, there is a certain minimum allowable volume of the waste form per 1 kg of reprocessed SNF, at which the resulting glass compound corresponds either to the regulatory indicators [4], if it is, for example, aluminum-phosphate glass, or to the experimentally evidenced acceptable radiation load limits [6] in case of borosilicate glass. This minimum volume will, obviously, depend on the isotopic composition of SNF subject to reprocessing, on its pre-reprocessing cooling time, on the reprocessing method (technology) (primarily on the depth, i. e., the efficiency of target element separation during SNF reprocessing), and, finally, on the separation degree assuming its further intermediate storage or potential future afterburning of some isotope fractions present in SNF (for example, minor actinide fractions — MA).

According to RW acceptance criteria for disposal (NP-093-14), waste of the first and second classes (solid high-level and long-lived intermediate-level waste) shall be disposed of in deep geological formations. Waste belonging to the third and fourth classes (solid intermediate-level and low-level waste) may be disposed of in near-surface repositories.

Tables 2 and 3 exemplify the calculated composition of SNF from a VVER-1000 reactor unit with a burnup of 50 GW-day/t U and a cooling time of 7 years showing the main elements or groups of elements considered of interest during the reprocessing and fractionation, as well as the calculated composition of the raffinate, which is expected to be generated from the reprocessing of this fuel according to the basic PDC flowchart adopted for the Zheleznogorsk site [7].

Table 2. Calculated composition of SNF from the VVER-1000 reactor

Element (group)	Content indicators in SNF		
	Mass, kg/t	Activity, Bq/t	Heat release, W/t
U	824	$2.01 \cdot 10^{11}$	0.07
Pu	10.5	$4.77 \cdot 10^{15}$	205
Np	0.64	$1.35 \cdot 10^{12}$	0.1
Am	0.70	$6.83 \cdot 10^{13}$	60.7
Cm	0.07	$1.95 \cdot 10^{14}$	185
Cs+Sr (including daughter nuclides)	4.39	$1.55 \cdot 10^{16}$	1,370
Other FP	41.0	$2.42 \cdot 10^{15}$	160

Given the depth of target element separation — uranium ($\geq 10^5$) and plutonium (neptunium) ($\geq 10^4$)

during industrial SNF reprocessing (Table 3), one can conclude that the volume of the borosilicate compound will be negligible (less than ml per kg of SNF) taking into account the experimentally proven acceptable radiation exposure during the deep disposal process (RW of the 1st hazard class) caused by this group of elements (Table 4). Thus, this factor can be largely neglected during further consideration of the disposal challenges.

Table 3. Calculated composition of raffinate from VVER-1000 SNF reprocessing according to the PDC flowchart

Content of elements, g/l						
U	Pu	Np	Am	Cm	REE	Zr
$1.8 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$	$2.7 \cdot 10^{-4}$	0.15	0.01	2.81	0.95
Cs	Sr	Ba	Tc	Mo	NM	HNO ₃ , M
0.69	0.21	0.48	0.02	0.78	0.71	4.0

Table 4. Minimum allowable volumes of highly active borosilicate compound intended for deep disposal

(calculations assume stability of 10 thousand years: 10^9 Gy for β , γ -radiation and $5.0 \cdot 10^{18}$ α -decays/cm³ for α -radiation)

Fraction of nuclides for solidification	RW category	Waste form type	Time of out-of-reactor cooling, years	Volume of solidified RW, cm ³ /kg SNF at burnup	
				50 GW-day/t	70 GW-day/t
Target product residues	HLW, Class 1	BSG	negligible	0.06	0.07
Minor actinides	HLW, Class 1	BSG	7	360	570
			37	760	1,050
			67	830	1,120
FP (AM)	HLW, Class 1	BSG	7	570	770
			37	280	370
			67	140	180
Total (excluding package volume)			7	930	1,340
			37	1,040	1,420
			67	960	1,300

Considering the above approach, minor actinides, on the one hand, and fragmental radionuclides, on the other hand, cause the generation of comparable minimum amounts of RW belonging to the 1st class with their volume being by 3–4 orders of magnitude higher than the one of those generated due to the remaining target nuclear materials (NM) (Table 4). Therefore, these key groups of elements should be consistently considered in the development of conditioning and disposal options, including as potential (priority) fractionation objects.

Based on the comparative analysis focused on the composition of HLW from the reprocessing of highly burnt fuel, the experimentally proven radiation exposure limits for borosilicate glass (BSG) considered the key waste form material currently accepted by the global community for HLW immobilization purposes and the criteria underlying the classification of solidified RW, one can conclude that at present time it is not possible to go without deep underground RW disposal option considering the current maturity level of SNF reprocessing technology [8]. The stage of RW Class 1 solidification alone yields in a compound volume which is considered comparable with the one of the SNF subject to reprocessing (Table 4). In accordance with the requirements of [4], the content of α -emitting radionuclides in the waste form should not exceed 0.2% by weight. A calculation showed that if the acceptable mass fraction of α -emitters was taken as a limiting factor in the compound formation, the volume of the glass waste form for MA would be noticeably less than the minimum volume due to a possible radiation exposure (Table 5).

Table 5. The minimum volume of a glass-like waste form intended for the disposal of a MA fraction limited by the acceptable mass fraction (0.2%) of alpha emitters

Time of out-of-reactor cooling, years	Volume of solidified RW from VVER-1000 SNF reprocessing, cm ³ /kg SNF at a burnup level of	
	50 GW-day/t	70 GW-day/t
7	260	420
37	420	610
67	460	650

Data in Tables 4 and 5 indicate that at the first stage of deep RW disposal the minimum required BSG volume depends on the absorbed energy from the decay of radioactive fission products (FP), primarily isotopes of alkali and alkaline earth metals (AM and AEM). Subsequently this minimum level according to the radioactive components depends on the availability of MA in the waste. Against the background of other factors, after 3–4 decades of pre-reprocessing SNF storage, the effect of AM and AEM isotopes on the glass mass ceases to play a key role, and after 60–70 years, the volume of glass depending on the fission products will amount to one-fifth of the compound volume depending on the MA content. Literature sources also evidence [9] that alpha-emitters become critically important in terms of the absorbed dose rate for borosilicate glass and the energy release in the compound at the turn of some 100 years of storage.

Moreover, data in Table 4 evidences that even though an important part of FP decays, in the time interval of up to 40–50 years, out-of-reactor storage of SNF not subjected to reprocessing causes a noticeable increase in the RW volume requiring deep underground disposal, which is explained by a sharp increase in the amount of ²⁴¹Am being a decay product of ²⁴¹Pu (Figure 1).

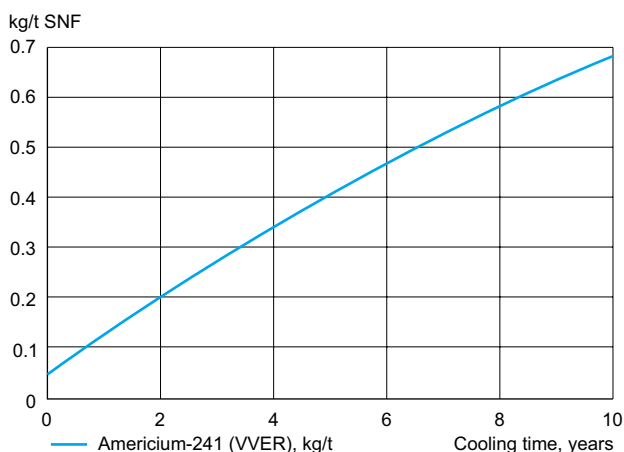


Figure 1. Accumulation trend for americium-241 in VVER-1000 SNF considering the option of its storage without reprocessing

Table 6. Minimum allowable volumes of intermediate-level borosilicate glass for near-surface disposal

Isotope (isotope group)	Half-life, years	Cooling time, years	VVER SNF activity (burnup 70 GW-day/t), Bq/kg	Minimum acceptable volume of solidified RW Class 3, cm ³ /kg
^{134,137} Cs + ⁹⁰ Sr (with daughter nuclides)	About 30	7	2.1·10 ¹³	7.8·10 ⁵
		37	9.6·10 ¹²	3.6·10 ⁵
		67	4.7·10 ¹²	1.8·10 ⁵
		97	2.4·10 ¹²	8.7·10 ⁴
		217	1.4·10 ¹²	5.2·10 ³
¹³⁵ Cs	2.3·10 ⁶	–	3.4·10 ⁷	1.3·10 ⁵
¹⁵¹ Sm	87	7	1.8·10 ¹⁰	6.8·10 ⁵
		67	1.2·10 ¹⁰	4.3·10 ⁵
		97	9.2·10 ⁹	3.4·10 ⁵
		217	3.7·10 ⁹	1.4·10 ⁵
		307	1.8·10 ⁹	6.8·10 ⁴
⁷⁹ Se	6.5·10 ⁴	–	1.1·10 ⁷	4.0·10 ²
⁹³ Zr	1.5·10 ⁶	–	1.1·10 ⁸	4.2·10 ⁵
⁹⁹ Tc	2.1·10 ⁵	–	7.7·10 ⁸	2.9·10 ⁴
¹⁰⁷ Pd	6.5·10 ⁶	–	9.3·10 ⁶	3.5·10 ²
¹²⁶ Sn	1.0·10 ⁵	–	8.1·10 ⁷	3.0·10 ³

Relatively short half-lives of the main heat-generating nuclides — cesium-137 and strontium-90 indicate that the option providing for their separation into a separate fraction followed by controlled decay storage and further disposal in near-surface repositories may be considered feasible. Table 6 shows the calculated minimum allowable volumes of glass provided the conditioning of waste from VVER-1000 SNF reprocessing compared against the option of RW Class 3 disposal in a near-surface repository [8].

The data show that AM and AEM (^{134,135,137}Cs + ⁹⁰Sr) when separated into a separate fraction may form a waste form volume considered relatively acceptable for the near-surface disposal (about 2 liters of BSG/kg SNF) only after 300 years of controlled storage; whereas, at the initial stage, this fraction will be categorized as RW with high specific heat release. In addition, it should be borne in mind that the ingress of ²⁴¹Pu and ²⁴¹Am isotopes into the separated fraction in an amount of only 1 µg/L during the formation of Class 3 RW will lead to an almost 1.5-fold increase in the waste form volume.

It should be noted that high amounts of the compound available at the stage of RW Class 3 generation cause the formation of active fission products, which are usually overlooked when the problems of fractionation in particular and RW conditioning in general are considered. These fission products primarily include ¹⁵¹Sm and ⁹⁹Tc.

Table 7 summarizes the consequences of the fractionation option. This option provides for the extraction of a minor actinide fraction from the HLW

Table 7. Minimum volumes of high activity borosilicate glass for deep disposal

Fraction of nuclides for solidification	RW category	Matrix type	Time of out-of-reactor cooling, years	Volume of solidified RW, cm ³ /kg SNF at burnup	
				50 GW-day/t	70 GW-day/t
U+Pu residues	HLW, Class 1	BSG	negligible	0.2	0.2
Minor actinides			7	0.4	0.6
			37	0.8	1.0
			67	0.8	1.1
FP			7	570	770
			37	280	370
			67	140	180
Total (with no account of the package volume)	7	570	771		
	37	281	371		
	67	141	181		

generated from VVER-1000 SNF reprocessing with an extraction degree of at least 10^5 and MA recycling into the fuel cycle during RW vitrification into a Class 1 waste form according to the hazard level either with or without preliminary cooling. Obviously, considering the RW volumes requiring disposal, it seems to be the most compact option compared to all those considered earlier.

When the prerequisites for the formation of a fractionation strategy for HLW generated from SNF reprocessing are considered, one should also take into account the “raw isotope” aspect of the problem. A number of literature sources [10] consider the idea of using HLW as a vital source of active and inactive isotopes useful for industry.

Unfortunately, ^{137}Cs separated from highly burnt SNF is usually not suitable for the production of ionizing radiation sources that are in demand on the market due to the high contamination with another cesium isotope with hard gamma radiation, namely, ^{134}Cs . ^{241}Am from HLW is basically considered unsuitable for the production of sources, since it is available as a mix with ^{243}Am . ^{147}Pm separated from highly burnt SNF is not used for RS fabrication purposes due to heavy ^{146}Pm contamination. Therefore, considering all radioactive isotopes found in the HLW generated from the reprocessing of highly burnt SNF from power reactors, only ^{90}Sr and ^{144}Ce turn out to be suitable for the production of radioisotope heat sources. However, to date their production in Russia has been stopped completely. The economic efficiency of non-radioactive element extraction from HLW, even of such rare and expensive ones as, for example, rhodium or ruthenium, is not yet visible in the foreseeable future against the backdrop of the existing supply and demand. Thus, in the development of a fractionation strategy, the interests in the isotope production can be currently neglected.

Potential options of the HLW fractionation strategy and their feasibility assessment

Taking into account the aspects discussed above, the following fundamentally possible options associated with the management of HLW generated from SNF reprocessing have been stated in the literature [11] (three of them include fractionation):

- no fractionation — all nuclides are immobilized into a single waste form;
- Proryv project — extraction of actinides by 99.9–99.99% (U, Pu, Np, Am, and Cm) from the initial SNF and RW solution (both during the PUREX process and at the fractionation stage) and solidification of all other FPs into borosilicate glass (heat-generating HLW);
- optimized Proryv+ — the Proryv approach is supplemented by FP vitrification involving two stages: initially into a glass-like granulate with the

standards for the content of β -, γ -emitters (i. e., the radiation resistance limit) being exceeded and its subsequent remelting (restoration of the glass structure) into a monolithic waste form after 55–60 years of storage (during this time, 3/4 of the dose from Cs, Sr and short-lived FP will be absorbed, thus, the radiation resistance limits will be complied with for the newly formed waste form);

- fractionation of MA+FP — extraction of all actinides (target products and MA) from the initial SNF and RW solution by 99.9–99.99% (U, Pu, Np, Am, Cm), separation of the Cs–Sr fraction for solidification into a RW Class 3 waste form (300 years after reprocessing) and vitrification of all other FP with MA residues as RW Class 1.

Calculations show that the HLW disposal cost, for example, given the reprocessing option applied to highly burnt mixed nitride fuel from the BREST-OD-300 reactor provided that only MA are subject to fractionation, turns out to be 1.5–2 times lower compared to the costs of the non-fractionation option. At the same time, the cost of deep fractionation options (MA and Cs–Sr) turns out to be almost an order of magnitude lower than the one providing for no fractionation. The minimum disposal cost is expected under the option of MA and FP (short-lived fraction) fractionation and subsequent near-surface disposal after most of the activity decays (Table 8).

Table 8. Comparative characteristics of processing and conditioning options for the RW from BREST-OD-300 SNF reprocessing (12% burnup and 2 years of decay storage)

Option	Volume of solidified RW fractions, cm ³ /kg SNF		Estimated cost of disposal in 2021 prices (thousand rubles/kg SNF)
	Actinides	Fission products	
No fractionation	1.1·10 ³ (Class 1)	1.3·10 ³ (Class 1)	3.6
Proryv	2.0 (Class 1)	1.3·10 ³ (Class 1)	2.0
Proryv+	2.0 (Class 1)	284.0 (Class 1)	0.44
MA+FP fractionation (AM and AEM)	2.0·10 ³ (Class 1)	120.0 (Class 1) + 8.3·10 ³ (Class 3 Cs+Sr)	0.34
Renouncing the fractionation and deep disposal option	7.4·10 ⁸ (Class 3)	1.4·10 ⁷ (Class 3)	1.2·10 ⁵
MA separation and renouncing the deep disposal option	8.4·10 ⁵ (Class 3)	1.4·10 ⁷ (Class 3)	2.4·10 ³

It should be noted that Table 8 takes no account of the costs associated with 60 years of vitrified

HLW storage and glass re-melting under the Prorvy option, as well as 300 years of controlled short-lived fraction compound storage (until the decay of cesium and strontium and their further transfer to near-surface disposal) under the MA+FP fractionation option. Given these circumstances, the final estimates may be somewhat different.

Nevertheless, it seems obvious that the options renouncing the idea of deep disposal, even those considering the option of preliminary actinide separation, prove to be unacceptable both from the engineering (compound volume) and financial perspectives.

A cross-analysis of all challenging aspects resulted in the following postulates drawn regarding the current vision of the fractionation strategy:

- long-term out-of-reactor storage of SNF without its reprocessing is at best impractical. Storage times prior to SNF reprocessing, including fractionation, should be minimized;
- fractionation of HLW from SNF reprocessing providing for the separation of minor actinide fraction seems appropriate from all points of view. At the first stage, when the challenge associated with minor actinide afterburning is not yet resolved, it may be acceptable to separate MA along with rare earth elements (REE) with an intermediate storage provided for the combined fraction;
- fractionation of HLW from SNF reprocessing and separation of cesium-strontium (heat-generating) fraction seems to be economically efficient;
- according to primary estimates, the most cost-effective option involves the solidification of the cesium-strontium (heat-generating) fraction after their decay into a Class 3 waste form. However, in this assessment a number of factors have not been taken into account (estimation error) and therefore it cannot be unambiguously proposed as the best option for the Russian SNF. At the same time, this option may turn out to be feasible for foreign customers in case if only the compound with a short-lived fraction (equivalent to the integral SNF activity) is returned to the SNF supplier country. In this case, the degree of the cesium-strontium fraction purification from minor actinides should be quite high.

As for the engineering tools required to implement the discussed strategy in addition to the establishment of appropriate obviously needed capacities, the time of out-of-reactor SNF storage before its reprocessing can be reduced, for example, through high-temperature SNF treatment (HTT) put at the head of reprocessing. Figure 2 shows a diagram of operating capacities available at plant RT-1 (PA Mayak) and those of the pilot demonstration center (PDC) expected to be commissioned

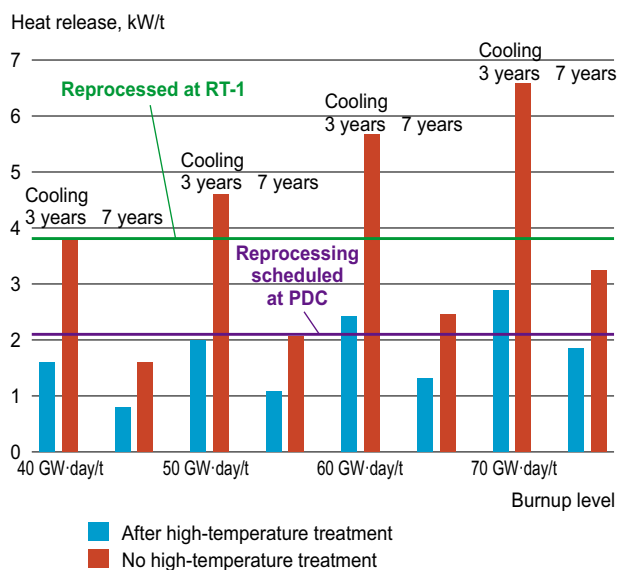


Figure 2. Influence of high-temperature treatment ($>1,200\text{ }^{\circ}\text{C}$) on the heat release of VVER-1000 SNF considering different burnup levels and cooling times

in the coming years and designed to accept SNF with different heat-release levels for reprocessing [7]. The technologies adopted at RT-1 plant are designed to reprocess fuel with a heat release of slightly less than 4 kW/t. According to the basic flowchart, the PDC is expected to treat highly concentrated NM solutions. In this regard, the maximum heat release of SNF, which can be accepted for reprocessing, is almost one half as high as the one indicated for PA Mayak.

Considering the heat release acceptability level, the data presented in the diagram indicate that after high-temperature treatment RT-1 can reprocess SNF with a burnup of up to 70 GW-day/t and a cooling time of only 3 years or even less. Given a cooling time of 7 years, fuel with a same burnup level is also considered suitable for reprocessing at PDC. If no high-temperature treatment is applied, SNF after three years of cooling can be reprocessed at RT-1 if its burnup does not exceed 40 GW-day/t; in case of PDC this fuel is considered generally unacceptable. Whereas after 7 years of cooling this fuel is considered acceptable if its burnup level does not exceed 50 GW-day/t.

Such an effect is quite understandable, given that the distillation of tritium, carbon, krypton and iodine during the high-temperature treatment can potentially reach 100%, in case of cesium and ruthenium – more than 95%, for technetium – more than 90%, for rhodium – more than 80%. At the same time, if the gaseous medium in which the high-temperature treatment of SNF occurs is adjusted, high-level stripping of molybdenum, barium, cerium, strontium, selenium and

tellurium becomes possible, i. e., the elements the short-lived isotopes of which are responsible for the SNF heat release in the first post-reactor years. Thus, the HTT can be considered not only a tool helping to reduce the SNF cooling time before reprocessing, but also a promising head pyrochemical fractionation stage.

Unfortunately, the feasibility of the HTT method in terms of its industrial application has not been demonstrated yet. Neither at RT-1, where the common hydrometallurgical SNF reprocessing method is applied, nor at the PDC, which is currently undergoing the pre-commissioning stage, high-temperature SNF treatment is provided for in the designs. At the same time, PDC designs state a limit for low-temperature voloxidation applied to remove and isolate tritium. If appropriate technology and equipment are successfully mastered by MCC specialists, it may be seen as a serious argument supporting the prospective integration of individual pyrochemical processing elements, including HTT, into common reprocessing flowcharts.

National developments in hydrometallurgical fractionation technologies have been analyzed: it was shown that the extraction technology based on the application of heteroradical phosphine oxide could be currently considered as a most studied and complete to provide joint separation of rare earth elements and transplutonium elements (TPE) [12].

To isolate an individual TPE fraction, the extraction technology based on diglycolic acid tetraoctyl-diamide (TODHA) seems to be the most developed one in this respect [13].

Finally, the cesium-strontium fraction can be isolated using an extraction technology based on chlorinated cobalt dicarbonyl (successfully implemented under a pilot project at PA Mayak in 1996–2003 [14]), or crown ethers (tested on a bench scale [15] both using mockup and actual solutions).

Conclusion

At the present stage of nuclear power development, fractionation is becoming a key element of the nuclear fuel cycle capable of providing environmentally acceptable and cost-effective management of high-level waste from SNF reprocessing.

To reduce the amount of RW subject to deep geological disposal and to minimize relevant costs, it's believed advisable to:

- reduce (given that relevant engineering evidence is provided) the pre-reprocessing SNF storage time;
- provide the separation of the MA fraction by at least 99.9% for their subsequent afterburning as fuel in FR and MSR (long-term controlled storage

of the MA fraction, i. e., transfer to storage facilities seems infeasible);

- separate Cs—Sr fraction via an engineering process given high-level purification from actinides (99.9%);
- study the prospects of long-term controlled RW Class 1 storage (Cs—Sr fraction) given further restoration of the glass-like waste form structure after 55–60 years;
- elaborate the near-surface option disposal for the Cs—Sr fraction and to demonstrate its safety;
- demonstrate the feasibility of a method that would provide computational and experimental evidence of a glass-like waste form resistance to an absorbed dose of over 10^9 Gy reached in 10 thousand years;
- continue the studies providing the experimental rationale required to increase the acceptable radiation load limits for the waste forms.

Practically a fractionation model may be considered providing for the primary extraction of actinides from HLW followed by the extraction of critical FP and an inverse model with no preliminary MA extraction.

Methods developed in Russia to extract some individual fractions of elements have been tested at least on a bench scale, were incorporated into promising designs of Russian enterprises and in the foreseeable future may help to launch the SNF reprocessing option involving HLW fractionation stage.

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