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Research Article

Analysis of radwaste accumulation in various scenarios of NP development

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Abstract

Within the framework of "Proryv" project a radiation-equivalent approach to radioactive waste management is being envisioned with U and Pu recycling and MA transmutation. Successful industry-wide implementation of the design approaches should be planned in order to avoid considerable financial and radiological encumbrances caused by the NFC final stage for two-component nuclear power system (NPS) under formation on the basis of thermal and fast reactors. In order to ensure a successful industry-wide implementation of the approaches being developed, the back-end of the NFC should not constitute considerable a financial and radiological burden for the emerging two-component nuclear power system (NPS).

This article addresses the problems concerning justification of radiological and technical-and-economic feasibility of MA partitioning and subsequent transmutation in FNR. The extent of MA accumulation as a result of TNR SNF reprocessing confirms the need for the introduction of MA partitioning technologies not only at all reprocessing plants planned for commissioning, but also at the plants now in operation. Based on available data, the study has shown that the implementation of the closed NFC with FNR contributes to significant reduction in the cost of disposal of radwaste compared to the scenario based exclusively on the development of VVER and open fuel cycle technologies. Recycling plutonium in fast reactors should be implemented in conjunction with MA to address environmental, non-proliferation and economic concerns of the back-end of advanced NFC. Within the scale of the future nuclear power system in Russia, an option such as this can only be realized on the basis of developing a FNR fleet.

Keywords

fast neutron reactors, minor actinides, fractionation, SNF reprocessing, radwaste

Introduction

Within the framework of "Proryv" project the back-end of the nuclear fuel cycle (NFC) is assumed to implement a radiation-equivalent approach to the management of radioactive waste (RW) with U and Pu recycling and minor actinides (MA) transmutation (Ivanow et al. 2021a, b; Kashirsky et al. 2022; Adamov et al. 2023). In order to ensure a successful industry-wide implementation of the design approaches, the back-end of the NFC should not constitute considerable a financial and radiological burden for the emerging two-component nuclear power system (NPS). In this respect, the closed nuclear fuel cycle infrastructure should be developed in a manner that takes into account both current and forecasted capabilities of spent nuclear fuel (SNF) reprocessing plants, which will be used for starting up advanced fast neutron reactors (FNR)

By now, the rationale for recycling nuclear materials, produced in the course of reprocessing SNF from thermal neutron reactors (TNR), in FNR has been confirmed from a radiological and analytical standpoint (Adamov et al. 2023; Ivanov et al. 2022a, b). For a successful transition to a two-component nuclear power system, the transformation of the back-end of the NFC is necessary, this being emphasized by the industry-level strategic program for the development of radiochemistry, that was developed to form and implement a series of R&D area sand support activities on SNF reprocessing and RW management. In this view, it is very important to justify radiological and technical-and-economic feasibility of MA partitioning for their further transmutation in FNR.

The main objective of the study is to identify the key differences between several probable open and closed nuclear fuel cycle development scenarios in Russia in regards to radioactive waste accumulation. The article presents the rationale for implementing partitioning technologies as fast as possible in order to decrease the amount of MA that would otherwise be accumulated in the resulting radioactive waste from SNF reprocessing.

Initial prerequisites for the scenario study

A scenario-based study was carried out in order to estimate the overall RW that could be accumulated by 2100 for two NPS development scenarios. The characteristics of scenarios based on FNR and closed nuclear fuel cycles (CNFC) are compared with a scenario with exclusive TNR development.

The change in the overall installed power capacity of nuclear power plants (NPP) until 2050 in all scenarios corresponds to the values indicated in the “target” scenario for the development of nuclear power in Russia, given in the “Strategy for the Development of Nuclear Power in Russia until 2050 and Prospects for the Period up to 2100” updated in 2021 (Strategy-2021) (Protocol of the Meeting of the General Committee of Science and Engineering Board of Rosatom State Corporation on the topic 2022). The installed capacity trend line after 2050 was adopted based on the assumption that about 6 units could be commissioned per a 5 year interval, which corresponds to commissioning rate adopted in the Strategy-2021 document. The lifetime of VVER and FNR power unit operation was set to 80 years (taking into account possible lifetime extension programs). RBMK power unit lifetime was extended by 5 years (45+5 overall) and it corresponds to the current available information per the General Layout of electric power facilities until 2035. Duration of temporary storage of SNF irradiated in TNR before its transportation to the reprocessing plant was set to 7 years.

Duration of the external NFC of FNR operating in steady state mode of CNFC (time interval from SNF unloading from reactor core to regenerating and loading the fuel back into the reactor) was assumed to be equal to 3 years.

The scenario with FNR and CNFC (Scenario 1) implies utilization and recycling of all currently available stockpiled reactor-grade plutonium, as well as Pu formed after reprocessing new TNR SNF (taking into account the option of using RBMK SNF) with the intent to develop a large-scale FNR fleet in Russia. After 2050 only FNR-based power units are introduced (about 6 power units per 5 years). The rate of reprocessing TNR SNF corresponds to ensuring a steady level of annual rate of reprocessing for TNR SNF. Relatively high average burnup values (up to 12% h.a.) of MNUP fuel were adopted for the calculation of FNR fuel cycle characteristics.

In regards to Scenario 1, the following prerequisites are taken into account in terms of the possibility of introducing MA partitioning technology at the TNR SNF reprocessing plants:

Scenario 1.1 – MA partitioning at all TNR SNF reprocessing plants;
Scenario 1.2 – MA partitioning is only performed at RT-2 (RT-1 and ODC are operating without MA partitioning);
Scenario 1.3 – MA partitioning technology is not implemented introduced at any TNR SNF reprocessing plants.

In all the above Scenarios (1.1, 1.2 and 1.3) MA produced in the course of TNR SNF reprocessing are recycled in full in CNFC.

Fig. 1 shows variation of the NPP installed power capacity assumed for the scenario with the gradual transition to FNR and CNFC technologies (Scenario 1).

The volume of the radioactive waste generated depends on the amount of reprocessed SNF of TNR and FNR, their characteristics, as well as the specific reprocessing technologies used (whether or not MA partitioning technology is present/not present at that plant). According to the results for Scenario 1, the following amounts of SNF should be reprocessed for the fuel supply of FNRs:

- About 80,000 tons of TNR SNF HM (RBMK included);
- ~20 000 tons of FNR SNF HM.

Figs 2, 3 show the results of calculation of TNR SNF reprocessing rate and TNR SNF stockpile reduction for Scenario 1.

In Fig. 4 the NPP installed power capacity adopted for the scenario based on both current and forecasted VVER technologies is presented. In this scenario, the SNF reprocessing option (without MA partitioning) is assumed with further long-term storage of regenerated nuclear material, which is considered as a valuable product for a theoretical NPS in the future.

The cumulative amount of reprocessed TNR SNF in Scenario 2 was calculated to be 124,000 tons of TNR SNF HM.

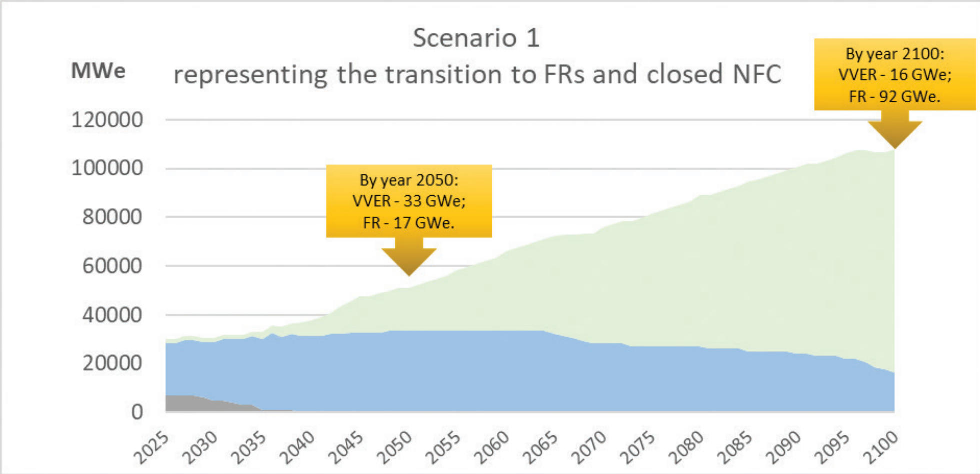

Figure 1. Growth of the NPP installed power capacity in the Russian Federation for Scenario 1 with the NPS transitioning to FNR and CNFC technologies.

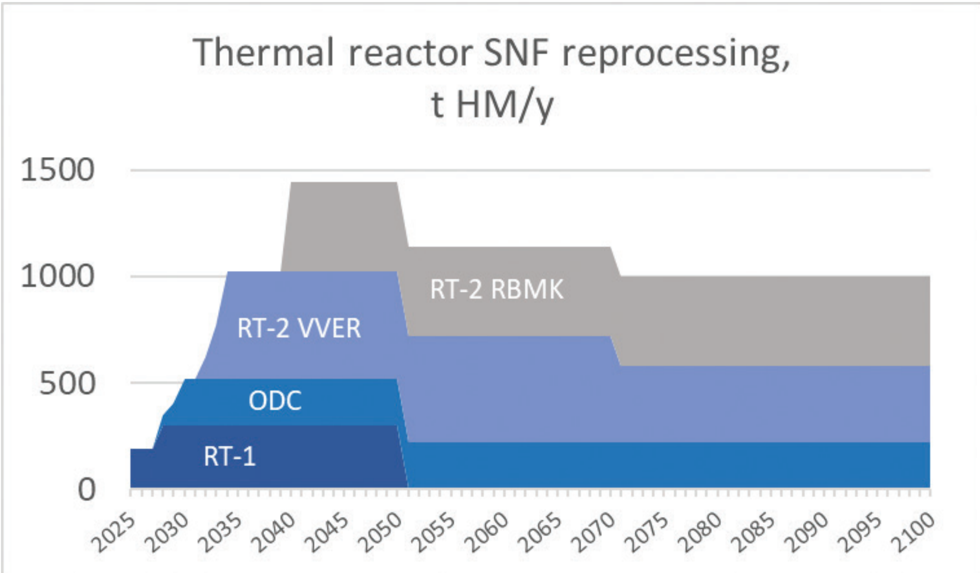

Figure 2. Variation of TNR SNF reprocessing rate.

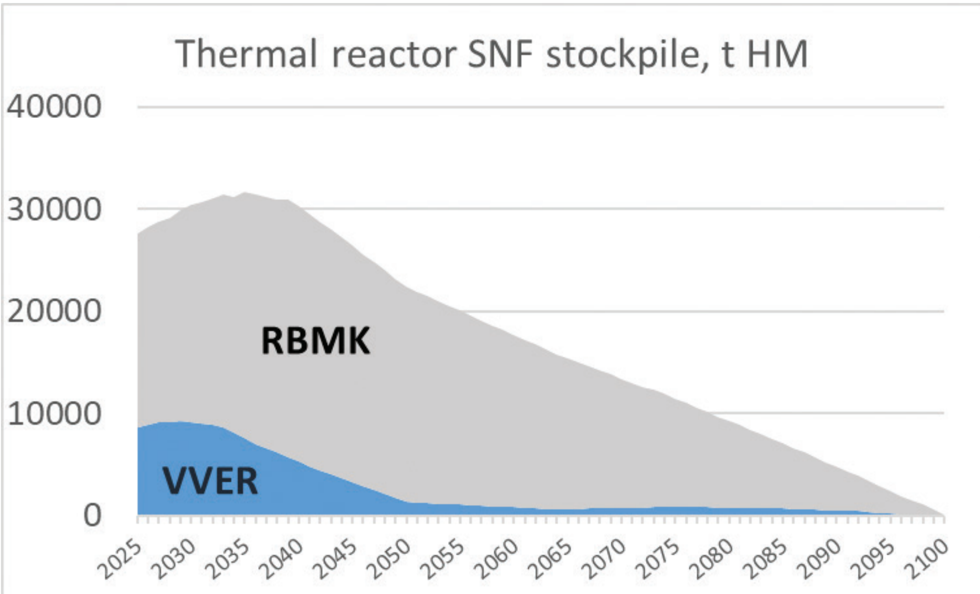

Figure 3. TNR SNF inventory change over time.

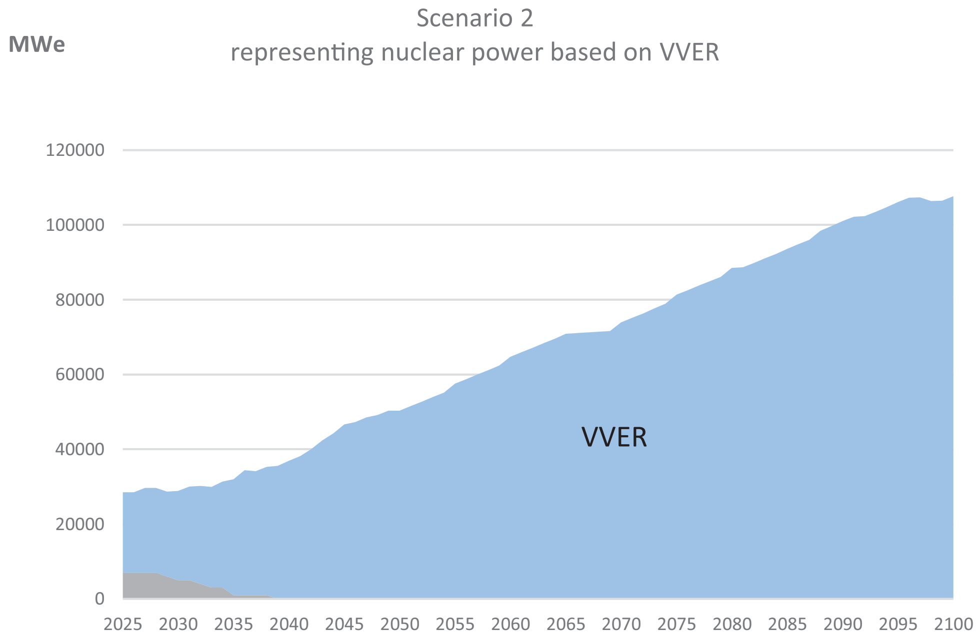

Figure 4. Growth of NPP installed power in Scenario 2 based on VVER only.

Determining radioactive waste volume

In order to determine the volume of Grades I-III radioactive waste from FNR SNF reprocessing, anoption named "Proryv" was considered, implying the possibility of disposing RW containing practically no MA after 10 years of storage, without glass overmelting. Regarding the RW from TNR SNF reprocessing, radwaste volume and grade are used in accordance with latest feasibility studies on creating a "Balanced NFC product".

It should be noted that:

- for the RW of FNR SNF reprocessing, volumes and grades of the radwaste resulting from reprocessing BR-1200 SNF from using mixed nitride uranium-plutonium (MNUP) fuel are taken into account (average fuel burnup is 12% h.a., fuel is stored one year in the in-vessel storage and then during two years out of the reactor before reprocessing, without glass overmelting); this RW is formed without MA inclusion (except losses at approximately0.1%);
- for the RW of VVER SNF reprocessing, volumes and grades of the RW resulting from reprocessing VVER-1000 SNF from using UO_2 fuel are taken into account (average fuel burnup is 50 MW·days/kg U, post-irradiation fuel storage duration before reprocessing is seven years, without glass overmelting, can optionally implement MA depending on scenario).

Adopted coefficient of the radwaste volume increase due to packaging was set to 2.0. The authors note that this coefficient should be used as a reference value only. With more data the coefficient can be determined more precisely at further stages of the project. Containers for the disposal of Grades I-II RW may affect the final (gross) RW volume to be sent for burial. So, taking into account the uncertainty factor in the calculations, the final (gross) RW amount may be 2 to 3 times higher than the reference values assumed for this calculation. Also, it should be noted that the range of the RW is subject to further clarification due to the latest Order of 29.10.2022 No. 1929 of the Russian Federation, which goes into effect in January 2024.

Fig. 5 shows RW volume estimates for annual unit operation (or for comparable annual production of electric energy). It is taken into account in the calculations that the annual fuel consumption of the NPP with VVER is about 23 t HM (Strategy-2021 data), and in case of FNR (with MNUP fuel burnup is equal to 12% h.a.) – 8.5 t HM (according to the latest results of development of Feasibility Study of Industry and Power Complex with BR-1200).

Calculating radwaste overall volume in the scenarios

Calculation results for the RW accumulation are presented in Figs 6–8.

According to the calculation results, the absence of MA partitioning at RT-1 and ODC would increase the volume of Grade I RW by about 34,000 m^3. If partitioning technology is absent at all TNR SNF reprocessing plants (RT-1, ODC, and RT-2) the volume of Grade I RW would be increased by 104, 000 m^3. The volume of Grade I RW in the scenario with nuclear power (NP) development on the basis of VVER (Scenario 2) exceeds by 76% the volume of Grade I RW in the scenario with NP development on the basis of FNR with partitioning applied at all reprocessing facilities.

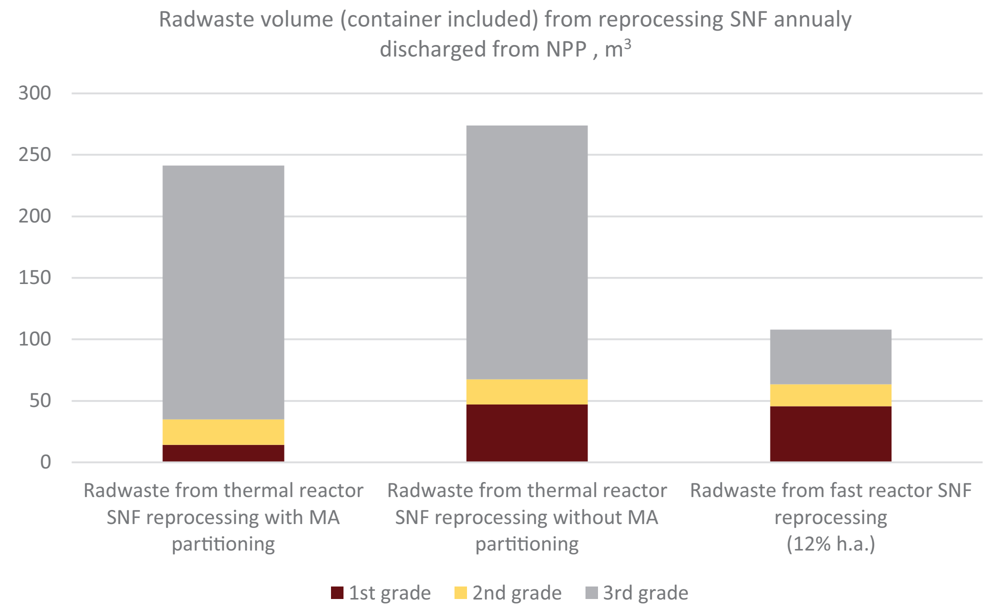

Figure 5. RW volume by grade fromreprocessing SNF annualy generated from FNR and TNR power units, m^3/year.

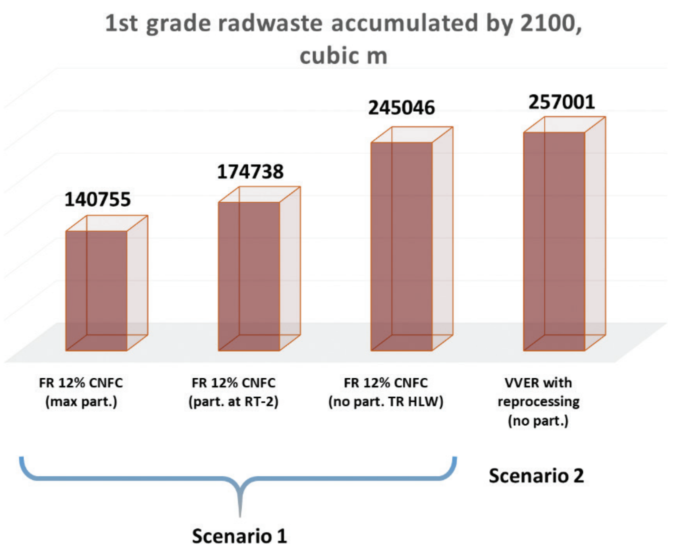

Figure 6. Accumulation of Grade I RW by 2100 in the scenarios under study.

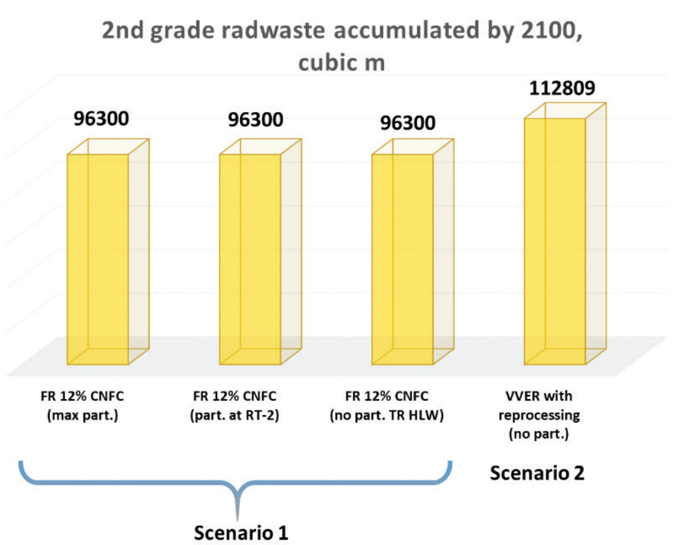

Figure 7. Accumulation of Grade II RW by 2100 in the scenarios under study.

Economical aspects based on radwaste accumulation in the aforementioned scenarios using available cost data reported in open literature as per information provided by the National Operator (NO) for 2023 is shown in Fig. 9.

It is shown in Fig. 9 that the financial burden of the back-end of NFC in terms of radwaste disposal costs in the scenario with NP development on the basis of VVER is about 50% higher than that in the scenario with FNR and CNFC with a maximum level of partitioning. It should be noted that current NO RW disposal tariffs are intended for the RW under federal ownership, so it does not include the cost of the full-scale infrastructure for the final disposal, and they are several orders of magnitude lower than those that are given in the available publications on the foreign projects (Final disposal of spent nuclear fuel in Olkiluoto Eura Print Oy 11/2011 2000; Report by the commission to the Council and the European Parliament on the progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects 2019; The Economics of the Back End of the Nuclear Fuel Cycle, Nuclear Energy Agency 2013; Thuillier 2020). In addition, there are no commercial capacity level facilities in operation in Russia for disposal of Grade I and II RW, and there are no such facilities under construction. Therefore, it can be stated that implementing a closed NFC strategy with FNR decreases uncertainties related to nuclear industry waste disposal.

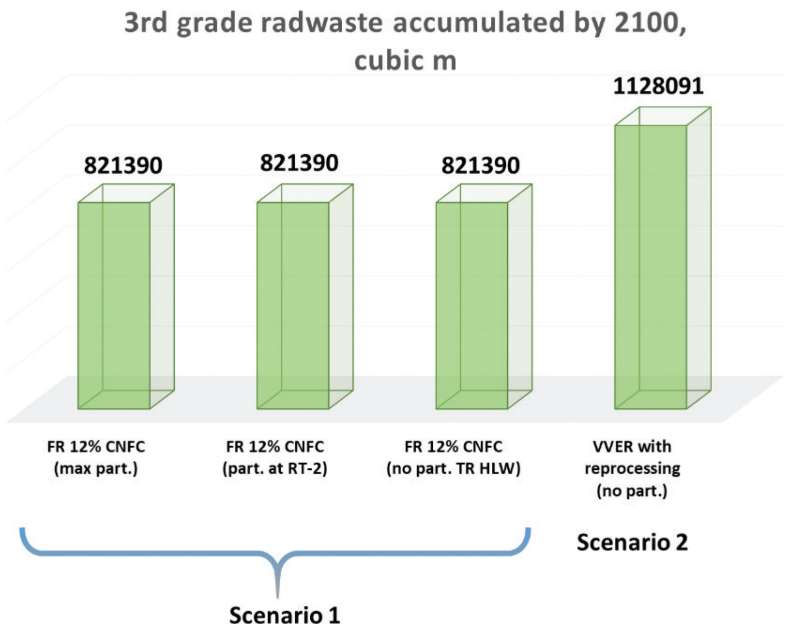

Figure 8. Accumulation of Grade III RW by 2100 in the scenarios under study.

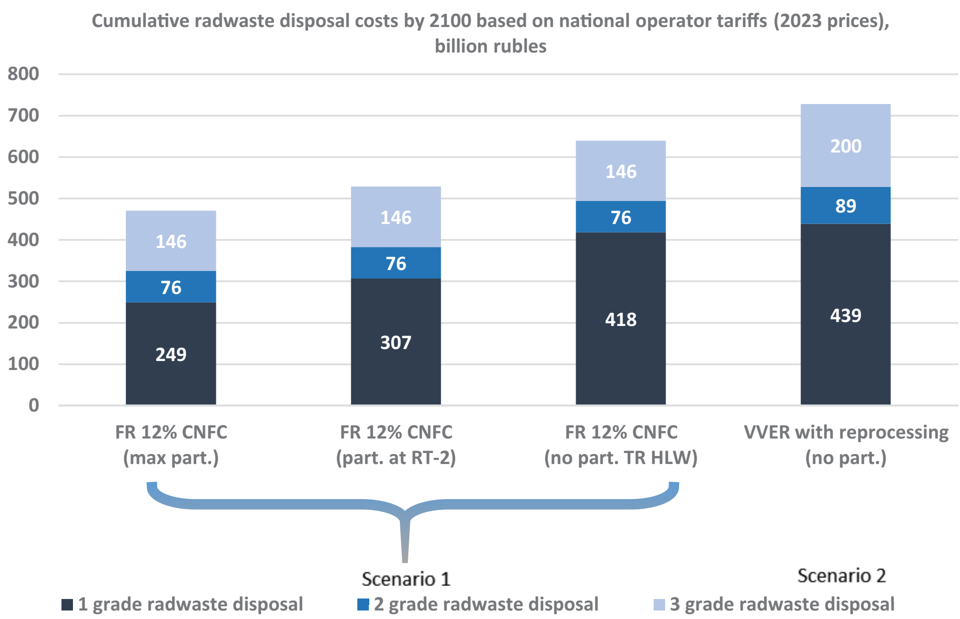

Figure 9. Total cost of radwaste disposal up to 2100 in the scenarios with SNF reprocessing.

Analysis of results

It should be noted that calculating the radioactive waste amount for the selected scenarios does not provide a comprehensive evaluation of the overall waste burden for the NO. In this respect, a radionuclide analysis of the radwaste content is must useful. Composition of minor actinides (TNR SNF MA are taken as an example) and their amount accumulated by 2100 for the scenarios under consideration are presented in Figs 10, 11.

Fig. 11 shows that the accumulated MA amount in the scenarios varies significantly depending on chosen strategy of SNF and RW management. About 35-170 t HM of MA can be accumulated in RW because of deferred decisions related to partitioning technologies. It was demonstrated earlier in (Ivanow et al. 2021a, b; Kashirsky et al. 2022; Adamov et al. 2023), that SNF disposal is an unacceptable approach to SNF management from radiation and radiological standpoints. In Table 1 some characteristics of key MA radionuclides present in SNF are given as compared to Pu-239 and U-235.

Table 1. Characteristics of Np-237, Am-241, Pu-239 and U-235 (The Economics of the Back End of the Nuclear Fuel Cycle, Nuclear Energy Agency 2013)

	Half-life, years	Specific power, W/kg	Distribution coefficient, l/kg	Critical mass
Np-237	$2.14*10^6$	Insignificant	5	56
Am-241	433,6 (in Np-237)	114	1,900	60
Pu-239	24.119	1.9	550	13
U-235	$7.04*10^8$	Insignificant	30	53

According to the above data, with time, almost all MA in RW will be transformed into Np-237. As it can be seen from Table 1, Np-237 has insignificant heat release, high migratory aptitude and very long half-life, as well as critical mass slightly exceeding that of U-235 (53). It means that disposal of RW containing rather large amounts of MA is hazardous not only in terms of radiological safety, but also from the nuclear proliferation standpoint. Disposal of RW containing large amounts of MA would most probably require the construction of a controlled RW geological repository for an indefinite period. Therefore, it would be increasingly difficult to consider a site like this

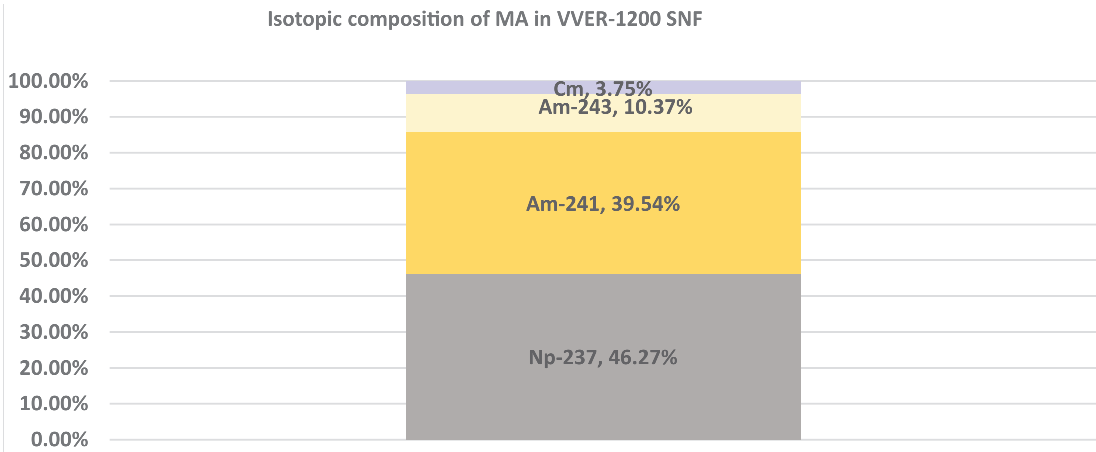

Figure 10. MA composition in VVER-1200 SNF.

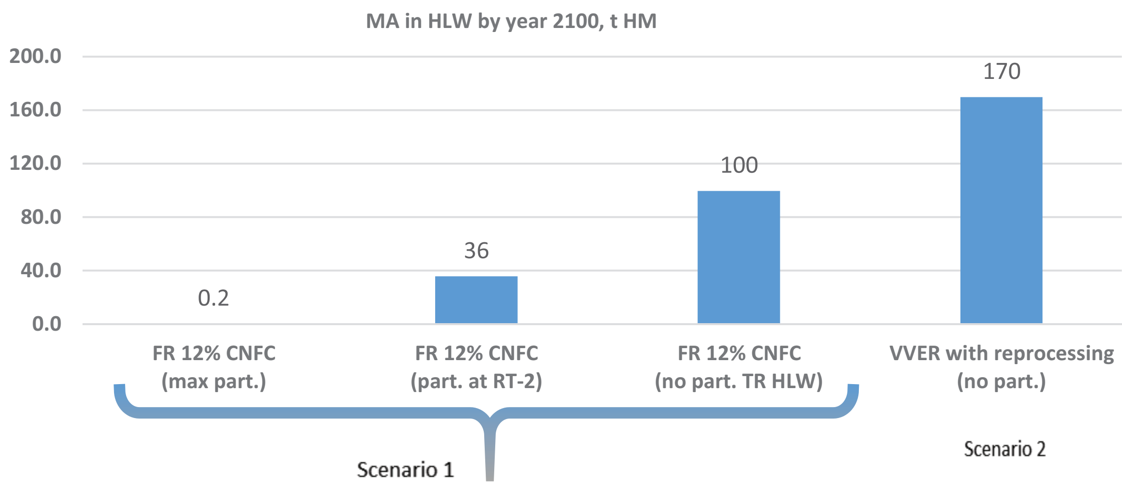

Figure 11. MA accumulation by 2100 in the selected scenarios.

"buried and forgotten". Taking into account the characteristics of materials being isolated, it is in the authors' opinion that maintaining a waste disposal site with a large amount of MA without supervision and suitable protection is unacceptable for security reasons.

Conclusion

Based on latest available data, studies have shown that implementing CNFC with FNR facilitates significant reduction of the cost of RW disposal as compared to a scenario with VVER development exclusively based on VVER and open fuel cycle technologies. Recycling plutonium in fast reactors should be implemented in conjunction with MA to address environmental, non-proliferation and economic concerns of the back-end of advanced NFC. Within the scale of the future nuclear power system in Russia, an option such as this can only be realized on the basis of developing a FNR fleet.

The amount of MA generated from TNR SNF reprocessing confirms that MA partitioning technologies are necessary not only at all new reprocessing plants, but also at all reprocessing plants that are now in operation.

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