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Radiation characteristics of REMIX fuel during multiple recycling in VVER-1000 reactors

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Abstract

Changes in the isotopic composition of three REMIX fuel types in the process of operation in a VVER-1000 reactor have been calculated. It has been shown that it is possible to recycle REMIX-A and REMIX-A2 fuel more than five times without a major decrease in its nuclear value. The equivalent dose rate from fresh REMIX fuel assemblies has been calculated depending on the recycle number and the fresh fuel decay time after fabrication. The relative contribution of different radionuclides to the equivalent dose rate has been analyzed. The calculation results for the buildup of ^{232}U and even Pu isotopes depending on the fuel recycle number are presented.

Keywords: REMIX fuel; Fuel cycle; VVER-1000 light-water reactor; Uranium; Plutonium; Uranium recycling; Plutonium recycling; Isotopic composition; Equivalent dose rate; Spent nuclear fuel.

Introduction

Recycling of reprocessed uranium and plutonium in thermal neutron reactors may provide for a more efficient use of nuclear fuel, a reduction in the amount of spent nuclear fuel (SNF) to be disposed, and a decrease in the risk of nuclear proliferation. Use of REMIX fuel is one of the options for the nuclear fuel cycle closing in the operation of VVER reactors [1]. However, recycling of plutonium is known to result in a buildup of its even isotopes in fuel [2], and uranium recycling leads to a build-up of ^{232}U [3]. Both cause the radiation characteristics of fresh FAs to deteriorate. Use of REMIX fuel in VVER reactors suggests recycling of both uranium and plutonium. The paper presents calculation results for the variation in the equivalent dose rate in the proximity of FAs with REMIX fuel during recycling. The equivalent dose rate in the proximity of FAs is an important contributor to the radiological hazard from nuclear fuel. Knowing it is essential in design of shipping casks, and in planning refueling operations in the fresh fuel region at a nuclear power plant.

Three types of REMIX fuel are considered in the paper: A, A2 and B. The REMIX-A fuel [1,4] is a non-separated mixture of reprocessed uranium and plutonium following the addition of 17–20 wt. % of enriched natural uranium (ENU) containing 19.75% of ^{235}U. The REMIX-A2 fuel differs from the REMIX-A fuel in a higher plutonium content [5]. For calculations, the plutonium weight content in the REMIX-A2 fuel is assumed to be 3%. Such an increase in the plutonium content makes it possible to reduce the amount of enriched uranium added after each recycle. The third fuel type, REMIX-B, [6] is fabricated from separated uranium and plutonium products obtained during SNF processing, with all of the extracted uranium being re-enriched and then added to the extracted plutonium. The plutonium content in this fuel is also 3%. This fuel is not recycled.

In this study, the change in the nuclide composition of the considered REMIX fuel types in the process of operation in a VVER-1000 reactor was calculated. The fuel burnup was calculated for an infinite FA grid using precision

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Table 1
Isotopic composition of initial uranium–plutonium regenerate.

Composition	^{238}U	^{235}U	^{236}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Content, kg/THM	973.72	8.58	6.04	0.30	6.42	2.71	1.40	0.83
Total, kg/THM	988.3			11.7				

Table 2
Isotopic composition of plutonium addition to REMIX-A2.

Composition	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Content, %	1.3	63.3	25.1	5.2	5.1

Monte Carlo codes. A 4-year reactor operation cycle was calculated. The equivalent dose from FAs was estimated by Monte-Carlo method. Neutron and gamma radiation contributions were taken into account. Other radiation types (α- and β-) do not contribute to the dose rate in the proximity of FAs, since electrons and α-particles have small path lengths and are delayed by the fuel cladding. The equivalent dose rates from FAs with the different REMIX fuel types were compared.

Multiple recycling of REMIX-A and REMIX-A2 fuels

The MCU code [7] and the MURE code [8] plus the MCNP code [9] were used to calculate the fuel composition after burn-up. To compare the performance of the codes, the REMIX-A fuel burn-up was calculated using both the MCU and the MURE+MCNP software packages. After the successful data verification, the REMIX-A2 fuel burn-up was calculated using MURE+MCNP, and the REMIX-B burn-up was calculated based on MCU.

A model of the TVS-2 M fuel assembly with mirroring boundary conditions was used for the calculations. The initial material for the REMIX fuel was the VVER-1000 spent uranium fuel with a burn-up of 49.2 GWd/THM (the average design fuel burn-up in an FA with an initial uranium enrichment of 4.33% after a 4-year fuel cycle). The FA irradiation time was 1200 effective days, and the decay time to the fabrication of reprocessed fuel was 5 years.

Fabrication of REMIX fuel requires uranium–plutonium regenerate to be extracted from the initial material. Its composition is given in Table 1.

During calculations, uranium with an invariable composition and an enrichment of 19.75% (a commercial product of JSC "SCC") was used as the initial material for the makeup fuel; in addition to highly-enriched uranium, plutonium extracted from the VVER-440 reactor spent fuel (from PA "Mayak") with an average burn-up of 36 GWd/THM was used for the REMIX-A2 makeup. The isotopic composition of the added plutonium is given in Table 2.

The REMIX burn-up was assumed to be 49.2 GWd/THM. For all recycles, the composition of the fresh REMIX fuel is adjusted such that to obtain an effective enrichment of 4.95%. The effective fuel enrichment is calculated with regard for the specific content of ^{235}U, ^{239}Pu and ^{241}Pu in the fuel and the content compensation factors for ^{236}U, ^{240}Pu and ^{242}Pu [10]. The calculation results for the REMIX-A fuel burn-up after five recycles are given in Table 3.

Since the REMIX-A fuel concept suggests the use of a non-separated mixture of uranium and plutonium, the plutonium content in the fuel increases with each recycle. It can be also seen that the fuel composition "deteriorates" with each recycle: there is an increase in the ^{236}U concentration which reduces the reactor reactivity, the content of fissionable Pu isotopes (^{239}Pu and ^{241}Pu) decreases, and the content of non-fissionable Pu isotopes (^{240}Pu and ^{242}Pu) grows. By the fifth recycle, the content of even plutonium isotopes increases from 33% to 40%. There is a growth in the buildup of ^{232}U whose decay products produce hard gamma radiation. After each recycle, there is an increase in the content of americium and curium being intensive neutron sources.

Table 3
U and Pu content (kg/THM) in REMIX-A fuel.

Composition	Recycle 1		Recycle 2		Recycle 3		Recycle 4		Recycle 5	
	Before	After	Before	After	Before	After	Before	After	Before	After
^{232}U	2×10^{-6}	5×10^{-6}	5×10^{-6}	8×10^{-6}	7×10^{-6}	10×10^{-6}	8×10^{-6}	1×10^{-5}	9×10^{-6}	1×10^{-5}
^{234}U	0.6	0.4	0.7	0.4	0.7	0.5	0.8	0.5	0.8	0.5
^{235}U	47.9	14.5	48.5	16.1	49.4	17.2	50.1	18.0	50.7	18.5
^{236}U	4.8	9.9	8.6	13.2	11.5	15.8	13.8	17.9	15.6	19.6
^{238}U	937.6	907.4	929.5	899.7	923.9	894.6	91.8	890.7	916.7	887.7
Σ(U)	990.9	932.2	987.2	929.4	985.4	928.0	984.4	927.1	983.7	926.4
Pu (even)	3.1	5.4	4.8	6.5	5.9	7.2	6.5	7.6	6.9	7.9
Pu (odd)	6.0	9.6	8.0	10.6	8.8	11.0	9.2	11.3	9.4	11.5
Σ(Pu)	9.1	14.8	12.8	16.9	14.6	18.0	15.6	18.7	16.3	19.2
Am+Cm	–	1.4	–	1.8	–	2.0	–	2.1	–	2.2
U + Pu	1000	947.0	1000	946.3	1000	946.0	1000	945.8	1000	945.5
Eff. enrich., %	4.95	1.66	4.95	1.72	4.95	1.75	4.95	1.76	4.95	1.76