

TRANSURANIUM ELEMENTS TRANSMUTATION IN VVER AND PWR TYPE OF REACTORS

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Received on December 30, 2024

Presented by Ch. Stoyanov, Corresponding Member of BAS, on February 25, 2025

Abstract

The expected renaissance of nuclear energy production puts the now postponed decision on long-term spent nuclear fuel handling on focus. In case of tripling the currently existing nuclear power generation of the countries that signed the relevant declaration on COP-28, Bulgaria among them, the high level radioactive elements of the spent nuclear fuel should be treated in such a way, that their quantity should be reduced dramatically before their final disposal. Chemical approaches to remove the long-lived radioactive isotopes from the spent fuel exist for years. The question for their further utilization yet remains. Furthermore, the nuclear reactions in reactors' cores lead to build-up of certain amounts of ^{239}Pu . With increasing the number of the spent fuel production this quantity cannot be neglected anymore. The possibility of returning these transuranium elements in the core of power reactors for further transmutation is investigated in this paper by means of numerical experiment. Contemporary codes and cross-sections are used. The results show that balance may be reached for most of the highly active transuranium elements. The investigated approach gives promising results for spent fuel handling perspectives.

Key words: transuranium elements, transmutation, power reactors

Introduction. Recent developments in fighting the climate change show that nuclear power is among the most vital options for reducing the greenhouse emissions from electricity production. Moreover it is the only currently available low-carbon option for providing base load power to the energy systems of the

The results from the scientific research, presented in this paper, are financed by the internal competition of TU-Sofia-2023 under contract No. NIS-231IP0014-02.

<https://doi.org/10.7546/CRABS.2025.04.02>

countries. Therefore a number of countries started nuclear power plant construction, and most of those who already have nuclear power plants (NPP) declared their readiness to triple their nuclear capacity by year 2050. Currently there are more than 400 nuclear power reactors, operating over the world. Tripling them will mean that by 2050 around 1200 units will be in operation. This will triple the produced spent nuclear fuel (SNF) and an inevitable need for its proper management [1] will arise. The increased amount of spent fuel may also render inadequate the option for long-term geological disposal of spent fuel that is untreated beforehand toward reduction of its volume and/or activity. Therefore, well-timed research has to be performed to explore the applicability and the effect of the options for spent fuel treatment. One such option is to return most of the transuranium elements [2] from the spent fuel in the core of conventional power reactor adding them to the fresh fuel enriched to working concentration of Uranium-235. Since most of the current fleet consists of pressurised water reactors, the ability of their cores to perform burning of fission product should be thoroughly investigated.

The other challenge that should be expected to arise is the build-up of plutonium in the spent fuel. Since the current fleet of power reactors mainly consists of PWRs, the amount of Pu generated in the spent fuel is of no major concern. But tripling the nuclear power capacity may lead to amounts that cause trouble from non-proliferation point of view. Some of the PWR designs are able to use plutonium contained MOX fuel [3] by default, therefore their ability to burn the plutonium generated by previous nuclear fuel usage should be investigated as well.

Based on the above, two options for addressing these challenges have been investigated in the presented research. The first one includes the burnup of highly active transuranium elements in the core of VVER-1000 power reactor. The second one investigates the possibility to minimise the highly active transuranium elements and the generated plutonium by loading them together with the fresh fuel in PWR reactor core.

Calculations. Two different models have been developed to evaluate the possibility to use power reactor cores for burning the transuranium elements and the generated plutonium. The first model represents VVER-1000 assemblies in an infinite lattice (Fig. 1). The assemblies are described using 23×23 hexagonal grid for the fuel elements with initial enrichment of 4.6 wt. % ^{235}U . The fuel assemblies include six burnable absorber rods (5 wt. % Gd). Three different concentrations of the transuranium elements have been dispersed in the fuel elements – from VVER-440 spent fuel with initial enrichment of 3.6 wt. % ^{235}U enrichment, from VVER-1000 Westinghouse fuel assembly with 3.81 wt. % ^{235}U enrichment, and from VVER-1000 TVEL assembly with initial enrichment of 4.6 wt. % ^{235}U enrichment. The transuranium elements have been aggregated for 1442-days long fuel campaign, power density of 41.6 kW/kgU and final burnup of the assemblies of 60 MWd/kgU.

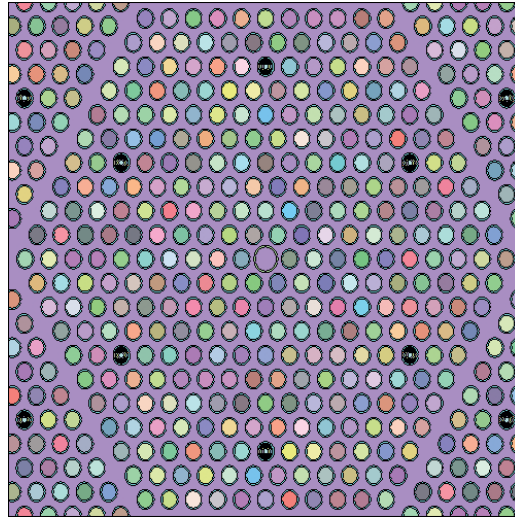


Fig. 1. Pin-by-pin geometry model of VVER-1000 hexagonal assembly in an infinite lattice for burnup calculation using SERPENT code

The transmutation cycle was evaluated after reenriching the ^{235}U up to 4.6 wt %. The same 1442-days long fuel campaign, power density of 41.6 kW/kgU and final burnup of the assemblies of 60 MWd/kgU was used for the transmutation.

The second model represents PWR assemblies in an infinite lattice (Fig. 2). The assemblies are described using 15×15 rectangular grid for the fuel elements

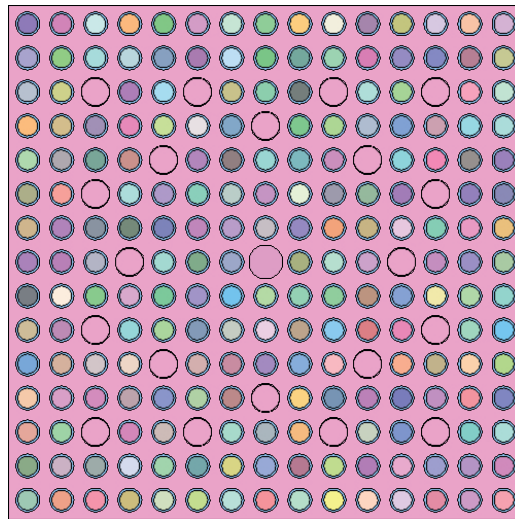


Fig. 2. Pin-by-pin geometry model of PWR rectangular assembly in an infinite lattice for burnup calculation using SERPENT code

with initial enrichment of 4.65 wt. % ^{235}U . The amount of the plutonium dispersed is approximately 0.4 wt. %. The transuranium elements and the plutonium, dispersed in the fuel have been aggregated for 1442-days long fuel campaign, power density of 41.6 kW/kgU and final burnup of the assemblies of 60 MWd/kgU.

Version 2.2 of the SERPENT code has been used in the calculations. It is a burnup and transport code that models the nuclear particles behaviour using the Monte Carlo Method [4]. Cross-sections libraries based on ENDF/B-VII.1 Evaluated Nuclear Data Library have been used for the calculations [5].

Results and discussion. The results for the amount of transuranium elements obtained after their reloading in the VVER-1000 core is presented in Table 1. The difference (Final/Initial)-1 in % for each of the spent nuclear fuels used as a source for the initial dispersion of the transuranium elements in the transmutation cycle is presented. It shows the relation between the initially loaded amount of transuranium elements and the amount available after burning the fuel up to 60 MWd/kgU. The amount is proportionally dispensed on the expense of the UO_2 content, thus similar initial values have been obtained.

T a b l e 1
Transmutation in VVER-1000 reactor core

Isotope	VVER-440 SNF source		VVER-1000 TVEL SNF source		VVER-1000 Westinghouse SNF source	
	Final mass in 1 cm ³ SNF,	Difference, %	Final mass in 1 cm ³ SNF,	Difference, %	Final mass in 1 cm ³ SNF,	Difference, %
	g		g		g	
Am-241	7.86E-04	13.84	7.87E-04	-4.00	7.86E-04	4.04
Am-243	4.57E-03	-3.74	4.52E-03	14.64	4.59E-03	-1.99
Cm-242	4.28E-04	1.65	4.30E-04	-2.86	4.29E-04	-5.28
Cm-243	2.09E-05	-3.15	2.13E-05	-1.31	2.12E-05	-1.61
Cm-244	6.14E-03	82.28	5.47E-03	110.25	6.12E-03	80.52
Cm-245	8.71E-04	168.93	7.59E-04	181.20	8.73E-04	145.05
Cm-246	4.56E-04	745.54	3.67E-04	1034.69	4.61E-04	755.20
Np-237	1.19E-02	30.45	1.22E-02	18.12	1.20E-02	25.69
Np-238	3.81E-05	17.69	3.92E-05	-9.14	3.86E-05	-10.64
Np-239	8.92E-04	-33.30	8.93E-04	-32.73	8.93E-04	-36.33
Total	2.61E-02	29.73	2.55E-02	28.51	2.62E-02	26.58

The obtained results show that the approach chosen for transmutation of the actinides aggregated in VVER-440 and VVER-1000 spent nuclear fuel has different influence on the different isotopes. For most of them, relative balance has been found, since the initial and final amounts differ within 10%, and few of the others are even reduced by up to 40%. The total amount of the investigated transuranium elements has increased only by approximately 30%, rather than 100% that shows the applicability of the selected method.

T a b l e 2
Transmutation in PWR reactor core

Isotope	Final mass in 1 cm ³ SNF, g	Difference, %	Isotope	Final mass in 1 cm ³ SNF, g	Difference, %
Am-241	6.37E-04	-1.39	Np-237	9.51E-03	11.46
Am-243	4.78E-03	7.54	Np-238	2.34E-05	-22.89
Cm-242	3.03E-04	-23.12	Np-239	6.01E-04	-52.00
Cm-243	1.42E-05	-29.71	Pu-239	4.44E-02	133.89
Cm-244	6.76E-03	114.46	Pu-240	2.11E-02	131.01
Cm-245	6.59E-04	117.41	Pu-241	1.60E-02	148.00
Cm-246	3.51E-04	596.01	Pu-242	1.37E-02	224.50

The results of the performed analyses of the applicability of a PWR reactor core to reduce the amount of the generated in VVER-1000 actinides, including 0.4 wt. % plutonium are presented in Table 2.

It is evident that the core of the PWR has similar capabilities for transuranium elements transmutation to the VVER, as should be expected, given the fact that both are thermal neutron reactors that use light water as a moderator. The results for the plutonium build-up show that the initially loaded amount is more than doubled during the transmutation cycle. Therefore a different approach should be used in order to properly treat the plutonium that is generated during the work of the VVER type of reactors. One such approach should be its usage as a secondary fuel in MOX fuel cite6 capable reactors. Nevertheless, equal increase of Pu-240, together with the build-up of Pu-239 has been found. This significantly increases the non-proliferation state of the spent fuel obtained after the transmutation performed.

Generally, only the Curium isotopes show significant build-up when transmutation is performed in the VVER-1000 and PWR reactor core. This is mainly related to the fact that they do not have significant cross-sections for interaction with thermal neutrons.

Conclusions. Precise modelling using the Version 2.2 of the SERPENT code is performed to evaluate the possibility to reduce the amount for final disposal of highly active transuranium elements, generated in the VVER-1000 reactor spent nuclear fuel. Two options have been investigated (1) VVER-1000 reactor core and (2) PWR reactor core. The results show that for most of the investigated isotopes, balance between their generation and burning is possible to be reached. For few of them a diminishment of their quantity is even observed after the transmutation cycle. Equal increase of the production of Pu-240 has been found, compared with the build-up of Pu-239 during the transmutation cycle. This significantly increases the non-proliferation level of the spent fuel that is to be obtained after the investigated transmutation process.

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